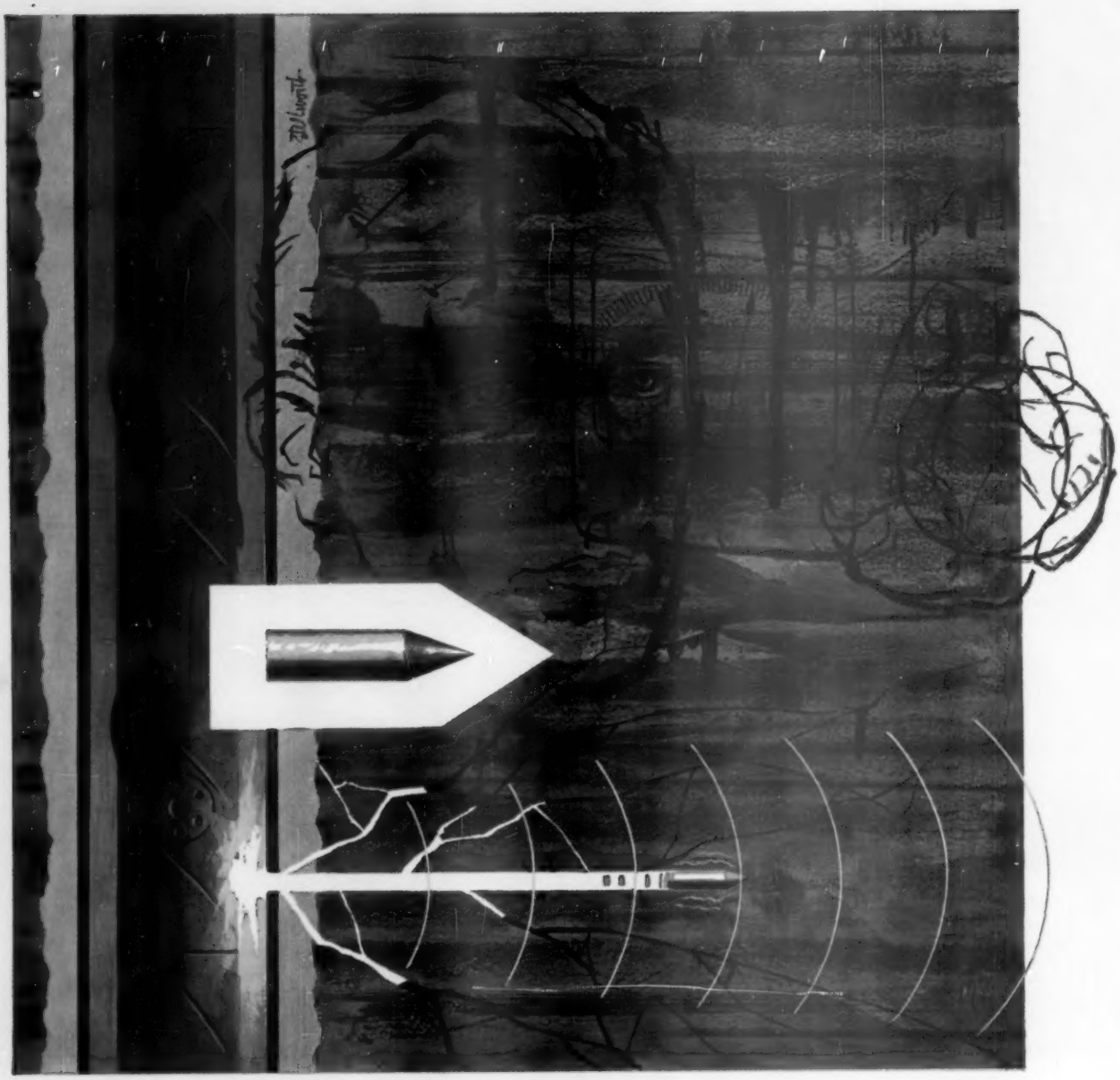
JOURNAL OF

PETROLEUM TECHNOLOGY

NOVEMBER 1955



The Schlumberger SUPER GUN

The Bullet Gun that set the standard for the Perforating Industry

IT'S AVAILABLE: Now every Schlumberger perforating location can serve your needs.
IT'S ECONOMICAL: You get premium perforating at standard prices.
IT'S POWERFUL: Engineered to give a maximum and uniform penetration.
IT'S RAPID: Up to 96 shots can be run on one trip in the hole.
IT'S FLEXIBLE: Choice of 2 guns and 4 bullet sizes with selective firing.

THE EYES OF THE OIL INDUSTRY **SCHLUMBERGER**
Well Surveying Corporation

SERVICE *still beyond the fee!*

When first this chart appeared in print, someone else was saying it... an independent petroleum association. We reproduce the chart, with emphasis on the low cost of cementing, to illustrate Halliburton's concept of service... service above all, service beyond the fee. Last month, an increase in cementing charges went into effect. But it is still the lowest cost service of any on this chart.

"Progress in Service through Research"

HALLIBURTON OIL WELL CEMENTING COMPANY

DUNCAN, OKLAHOMA

It takes a lot of acceptance by the petroleum industry for a service company to put thirty-three markers in a map of the United States — each representing the installation and 24-hour maintenance of a complete, modern core analysis laboratory.

In this case, the thirty-third pin is Core Lab's newest facility — *Liberal, Kansas* — to be opened soon.

As has been the case many times before, the sole reason for establishing a new lab in a particular area is the operators' need for basic formation data — accurately developed by qualified field personnel, interpreted under the supervision of an experienced area resident manager, and made available back at the well site as rapidly as possible. We repeat — without this continued demand for core analysis and its acceptance as a key to the chain of formation evaluation events to follow — we'd have thrown away our box of map pins a long time ago.

There is *no adequate substitute*, either electrical or electronical, for the advantages of directly examining the basic product — the formation and its contents. And the cost of obtaining the best core analysis data available is small when immediate and long-range benefits are balanced against the total cost of reaching an exploratory goal.

Liberal isn't the last. We've got a big box of pins.

CORE LABORATORIES, INC.
801 CORE STREET, DALLAS, TEXAS

CORE LAB
PETROLEUM RESERVOIR ENGINEERING

DALLAS, HOUSTON, CORPUS CHRISTI, MIDLAND, ABILENE, SAN ANTONIO, TYLER, TULSA, FORT WORTH, WICHITA FALLS, SHERMAN, OKLAHOMA CITY, ARDMORE, BARTLESVILLE, PAMPA, ARKANSAS CITY, GREAT BEND, NEW ORLEANS, SHREVEPORT, HATTIESBURG, LAFAYETTE, DENVER, BAKERSFIELD, CASPER, BILLINGS, WORLAND, STERLING, EL DORADO, LUBBOCK, FARMINGTON, LOVINGTON, MONAHANS, SAN ANGELO; CALGARY, EDMONTON, REGINA.

JOURNAL OF PETROLEUM TECHNOLOGY

NOVEMBER, 1955

OFFICERS • COMMITTEES

Chairman: R. B. Gilmore
DeGolyer & MacNaughton, Dallas, Tex.

Vice-Chairmen:
G. L. Yates
Amstutz and Yates, Wichita, Kan.
Phil J. Lehnhard
East Texas Engineering Assn., Kilgore, Tex.

EXECUTIVE COMMITTEE:

Burton Atkinson
Pishny and Atkinson, Fort Worth, Tex.
T. A. Atkinson
Douglas Oil Company, Los Angeles, Calif.
Roland Gouldy
Consulting Engineer, Wichita Falls, Tex.
George R. Gray
Baroid Division, National Lead Co., Houston, Tex.
Earl M. Kipp
The California Co., New Orleans, La.
John R. McMillan
Monterey Oil Co., Los Angeles, Calif.
W. D. Owsley
Halliburton Oil Well Cementing Co., Duncan, Okla.
John C. Calhoun, Jr.
Texas A&M, College Station, Tex.
Representing M.I.E.D.
Paul R. Schultz
Blackwell Oil & Gas Co., Tulsa, Okla.
Representing M.E.D.
Treasurer: T. A. Pollard
Magnolia Petroleum Co., Dallas, Tex.
Counsel: Robert E. Hardwicke
Hardwicke, Haddaway & Pope, Fort Worth, Tex.
Executive Secretary: Joe B. Alford
AIME, Dallas, Tex.

COMMITTEE CHAIRMEN:

Admissions: Virgil B. Harris
San Juan Oil Co., Dallas, Tex.
Advertising: W. D. Owsley
Halliburton Oil Well Cementing Co., Duncan, Okla.
Education: A. W. Walker
University of Tulsa, Tulsa, Okla.
General Editorial Committee: Roy H. Smith
Stanolind Oil & Gas Co., Tulsa, Okla.
Membership: Kenneth W. Robbins
Otis Pressure Control, Inc., Dallas, Tex.
Nominating: John R. McMillan
Monterey Oil Co., Los Angeles, Calif.
Transactions Editorial: K. C. Howard
Richardson & Bass, Fort Worth, Tex.
Student Activities: Shirley A. Lynch
Texas A&M, College Station, Tex.
Production Review: A. H. Chapman, Chairman
Arabian American Oil Co., Washington, D. C.
Milton Williams, Domestic Vice-Chairman
Humble Oil & Refining Co., Houston, Tex.
Technology: L. P. Whorton, Chairman
The Atlantic Refining Co., Dallas, Tex.
Roy A. Bobo, Drilling
Phillips Petroleum Co., Houston, Tex.
John H. Thacher, Petroleum Economics
California Research Corp., San Francisco, Calif.
Robert G. Parker, Production Engineering
Continental Oil Co., Oklahoma City, Okla.
R. K. Guthrie, Production Engineering
Seeligson Engineering Committee, San Antonio, Tex.
A. F. van Everdingen, Reservoir Engineering
Shell Oil Company, Houston, Tex.
R. A. Morse, Reservoir Engineering
Gulf Research & Development Co., Pittsburgh, Pa.

OFFICERS OF THE AIME:

President: H. DeWitt Smith
Vice-Presidents: Walter A. Dean, William Wallace Main, Jr., Lloyd E. Elkins, A. B. Kinzel, T. B. Counselman, Harold Decker.
President-Elect: Carl E. Reistle, Jr.
Past President: Leo F. Reinartz
Treasurer and Controller: Gail F. Moulton
Secretary: E. O. Kirkendall

CONTENTS

Field Case Histories

BIG MUDDY WATER FLOOD
by R. W. Haller 9

REPORT OF OPERATIONS NAVAL PETROLEUM RESERVE No. 1, ELK HILLS, 1945-1954
by Cmdr. F. W. Gooch, Jr., and R. H. Adams . . . 13

Petroleum Branch Affairs

REPORT AND INTERPRETATION 27
PETROLEUM ENGINEERING ENROLLMENT 28
PERSONALS OF PETROLEUM BRANCH MEMBERS 29
BRANCH CHAIRMAN REPORTS 1955 ACCOMPLISHMENTS . . 30
PROPOSED FOR PETROLEUM BRANCH MEMBERSHIP 35
MEET THE AUTHORS 39
EMPLOYMENT NOTICES 46

Technical Notes

FLUID MAPPER MODEL STUDIES OF MOBILITY RATIO
by Rex E. Cheek and Donald E. Menzie 49
THE CONCEPT "HYDRAULIC RADIUS" IN POROUS MEDIA
by G. J. Harmsen 53
A DEVICE FOR DETERMINING THE CONCENTRATION OF FORMATION TREATING ACIDS
by J. L. Huitt 57
A RESULT OF SP LOG INTERPRETATION
by Paulo Varjão de Andrade 59

Technical Papers

STUDIES ON PRESSURE DISTRIBUTION IN BOUNDED RESERVOIRS AT STEADY STATE
by C. S. Matthews and H. C. Lefkovits 182
CALCULATION OF UNSTEADY-STATE GAS FLOW WITHIN A SQUARE DRAINAGE AREA
by Jim Douglas, Jr., D. W. Peaceman and H. H. Rachford, Jr. 190
EFFECT OF MUD COLUMN PRESSURE ON DRILLING RATES
by A. S. Murray and R. A. Cunningham 196

On the Cover: The artist has portrayed the Christmas tree, often referred to as "the symbol of petroleum engineering."

EDITORS • STAFF

Advisory Editor: Roy H. Smith
Chief Production Engineer, Stanolind Oil & Gas Co., Tulsa, Okla.
Executive Publisher: Joe B. Alford
Editor: R. W. Taylor
Production Manager: Ann Krechman
Editorial Assistants: Virginia Daggett, Hattie Hight
Advertising Manager: Maurice D. Bratt
Advertising Assistant: Nelia McGranahan

Journal of Petroleum Technology is published monthly by the Petroleum Branch, American Institute of Mining and Metallurgical Engineers, Inc., at 800 Fidelity Union Bldg., Dallas 1, Tex. Entered as second class matter at the Post Office at Dallas, Tex. Domestic Subscription: North, South, and Central America, $8; foreign, $10; to AIME members, $6 (or $4 if in combination with subscription to either Journal of Metals or Mining Engineering). Single copies, 75 cents in U. S. A., $1, foreign; special issues, $1.50. Registered cable address, AIME. Printed in U. S. A. Views expressed herein are not necessarily those of the AIME.

THE AIME ALSO PUBLISHES MINING ENGINEERING AND JOURNAL OF METALS
COPYRIGHT 1955—AMERICAN INSTITUTE OF MINING & METALLURGICAL ENGINEERS, INC.

...One

BAKER

RETAINER PRODUCTION PACKER

PRODUCT NO. 415-D

SINGLE ZONE

PERMANENT-TYPE WELL COMPLETIONS

The Baker Retainer Production Packer has been used in nearly every production application, old or new, and promises to play an even greater role in future production applications.

Because it can also be used successfully as a squeeze tool, it is used in a variety of supplemental applications (such as testing, acidizing, formation fracturing, squeeze cementing, etc.) that might be required during the completion or work-over phase of a well. That is why the Baker Retainer Production Packer has been frequently referred to as the "universal" packer, because it is truly the *one* packer that can be used *for all* production and many supplemental applications.

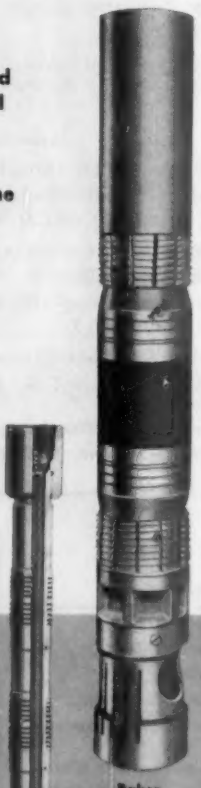
FEATURES

Can be run and set with the speed and accuracy of wire line, as well as on tubing or drill pipe.

Holds any pressure from either above or below that is safe for the casing, even under temperatures in excess of 300°F.

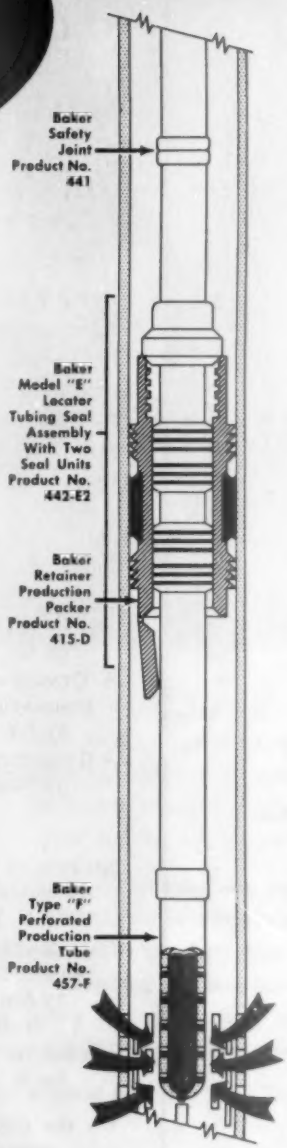
Pack-off is independent of set-down weight or tension. Tubing string is free; just pick up (or unlatch and pick up) to remove it.

When tubing is removed, flapper valve closes to isolate zone below packer.

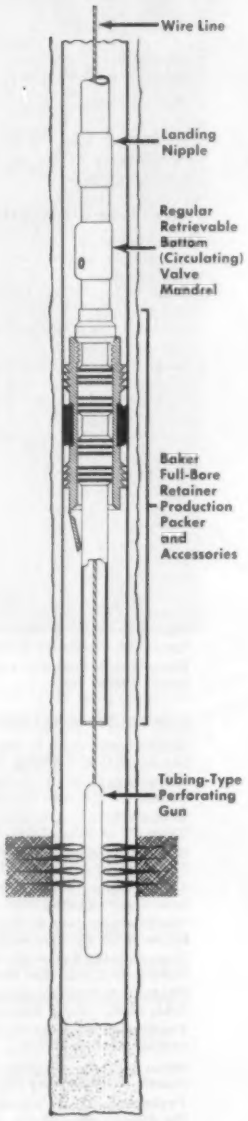


Baker Locator Tubing Seal Assembly Product No. 442-E2

Baker Retainer Production Packer Product No. 415-D


Baker Safety Joint Product No. 441
Baker Model "E" Locator Tubing Seal Assembly With Two Seal Units Product No. 442-E2
Baker Retainer Production Packer Product No. 415-D
Baker Type "F" Perforated Production Tube Product No. 457-F

Illustrates Packer set in casing with Locator Tubing Seal Assembly and Production Tube installed for single zone production.


Wire Line
Landing Nipple
Regular Retrievable Bottom (Circulating) Valve Mandrel
Baker Full-Bore Retainer Production Packer and Accessories
Tubing-Type Perforating Gun

Illustrates typical Permanent-Type Well Completion Hook-Up showing perforating operation through and below the Packer.

Successfully holds high pressures from above or below

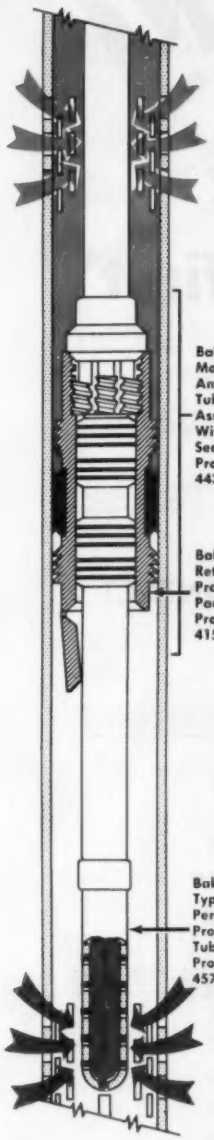
...at shallow or record depths

even under temperatures in excess of 300°F.

for all

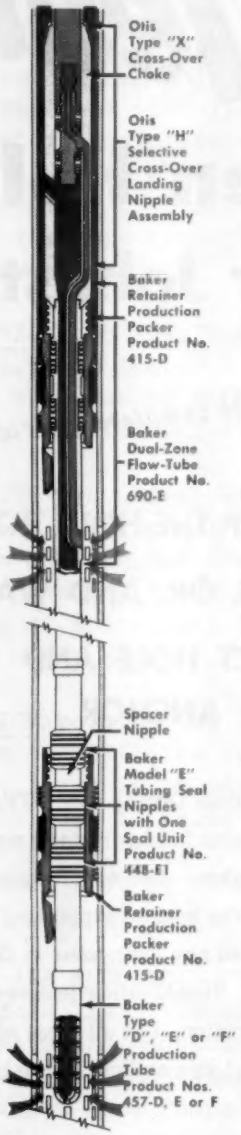
DUAL ZONE

SINGLE PACKER


Baker Model "E" Anchor Tubing Seal Assembly With Two Seal Units Product No. 443-E2
Baker Retainer Production Packer Product No. 415-D
Baker Type "F" Perforated Production Tube Product No. 457-F

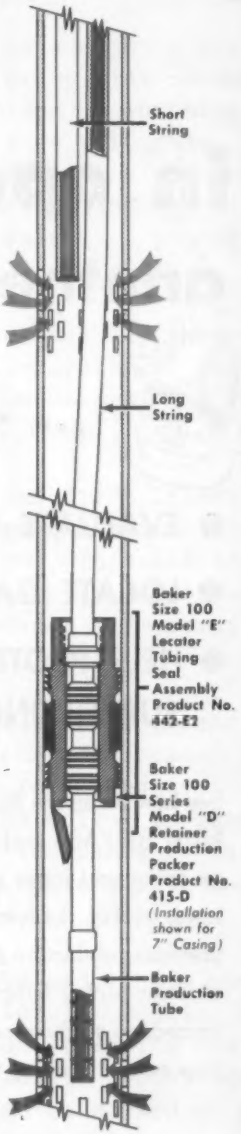
Illustrates Packer set in casing, with anchored production string for dual zone production. Tubing can be released from packer by rotating to right.

SELECTIVE CROSS-OVER


Otis Type "X" Cross-Over Choke
Otis Type "H" Selective Cross-Over Landing Nipple Assembly
Baker Retainer Production Packer Product No. 415-D
Baker Dual-Zone Flow-Tube Product No. 690-E
Spacer Nipple
Baker Model "E" Tubing Seal Nipples with One Seal Unit Product No. 448-E1
Baker Retainer Production Packer Product No. 415-D
Baker Type "D", "E" or "F" Production Tube Product Nos. 457-D, E or F

Illustrates selective two packer dual zone production hook-up (Baker-Otis) with Cross-over Choke installed. Flow pattern can be switched with Parallel Flow Choke.

PARALLEL STRING


Short String
Long String
Baker Size 100 Model "E" Locator Tubing Seal Assembly Product No. 442-E2
Baker Size 100 Series Model "D" Retainer Production Packer Product No. 415-D (Installation shown for 7" Casing)
Baker Production Tube

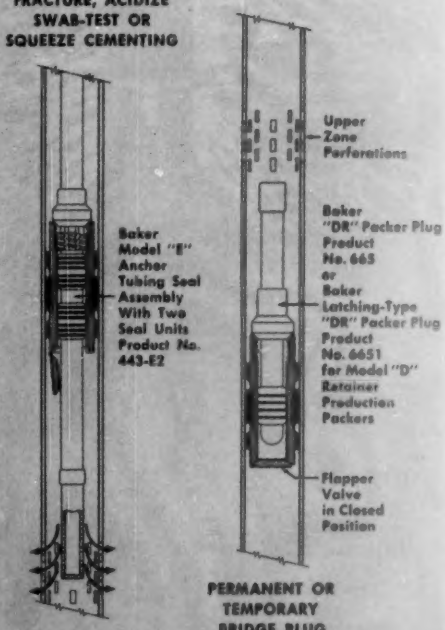
Illustrates simplest type of parallel string installation. Other installations involving two packers with full-opening tubing running through and below lower packer available.

SUPPLEMENTAL APPLICATIONS

WATER OR GAS INJECTION

The Baker Retainer Production Packer contains features that permit it to be used as a squeeze or testing tool as well as a temporary or permanent bridge plug. It is thus used in a variety of supplemental applications such as gas or water injection, testing, fracturing, acidizing, etc., that may be required either during the completion phase of a well or during a later phase.

FRACTURE, ACIDIZE SWAB-TEST OR SQUEEZE CEMENTING


Baker Model "E" Anchor Tubing Seal Assembly With Two Seal Units Product No. 443-E2
Upper Zone Perforations
Baker "DR" Packer Plug Product No. 665 or Baker Latching-Type "DR" Packer Plug Product No. 6651 for Model "D" Retainer Production Packers
Flapper Valve in Closed Position

PERMANENT OR TEMPORARY BRIDGE PLUG

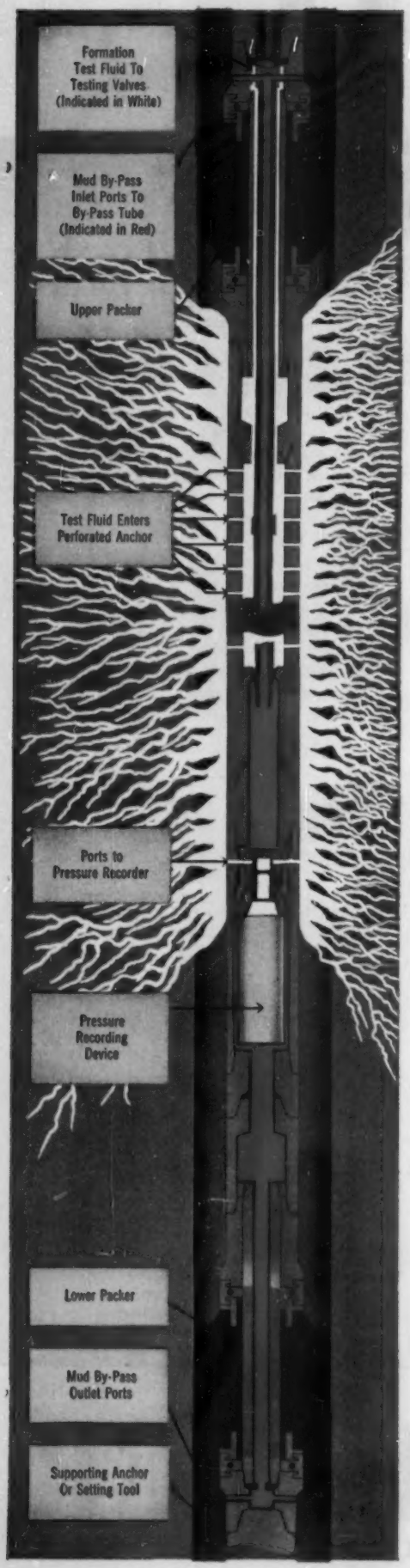
Send for complete information

A new 72 page catalog supplement is now available on the Baker Retainer Production Packer and its many features and applications. Write or ask your Baker Representative for Baker Catalog Supplement No. 502.

BAKER

OIL TOOLS, INC.

HOUSTON • LOS ANGELES • NEW YORK


Formation Test Fluid To Testing Valves (Indicated in White)
Mud By-Pass Inlet Ports To By-Pass Tube (Indicated in Red)
Upper Packer
Test Fluid Enters Perforated Anchor
Ports to Pressure Recorder
Pressure Recording Device
Lower Packer
Mud By-Pass Outlet Ports
Supporting Anchor Or Setting Tool

Straddle Testing

in open hole
another Johnston first*

Now, with complete confidence, you can...

- EVALUATE UP-THE-HOLE ZONES
- LOCATE GAS, OIL, AND WATER CONTACT
- HELP PROTECT HOLE AND SUPPORTING ANCHOR

See how Johnston Straddle Testing with STRADDLE MUD BY-PASS maintains full hydrostatic mud pressure on upper and lower packers—and on all formations below lower packer. Lessens the load on supporting anchor and prevents production from any lower zone in the event of lower packer failure. Should either packer fail, you get an immediate surface indication. Get all these advantages plus ease of running tool into and out of the hole.

*Johnston Straddle Testing with Straddle Mud By-Pass is covered by patent and patents pending. Another Johnston first!

for descriptive folder write to:

JOHNSTON TESTERS

first in drill stem testing

P. O. Box 98,
HOUSTON, TEXAS

LOS ANGELES, CALIF • CALGARY, CAN.

FORMATION AND CASING TESTING — JOHNSTON

ST 551

Pumping Progress Report

FOR HYDRAULIC ENGINEERS

An advertisement prepared by the Aldrich Pump Co., Member of Hydraulic Institute, U.S.A.

SPACE, in many pump installations, is a major problem. Another is the necessity for special foundations. When new installations are considered, these factors may dictate more elaborate construction than should be necessary. And for replacement or modifications of existing systems, they may require expensive piping and equipment changes.

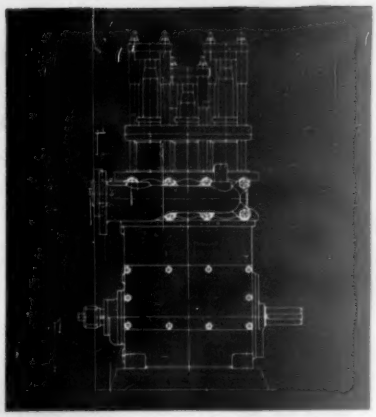
COMPACTNESS OF DESIGN, while often desirable, is not necessarily the answer. Simplicity of design — as in the case of ALDRICH Direct Flow Pumps — may be a better solution.

SIMPLICITY OF DESIGN brought about the first inverted Triplex and Quintuplex Pumps and ultimately Septuplex and Nonuplex Pumps. This Aldrich design innovation brought to pump users many economies of space, maintenance and operation they had never known.

INVERTED PUMP DESIGN permits the use of less expensive foundations. With the crankshaft located near the floor there is no need for expensive foundation work to raise the driver or lower the pump. Then, too, inverted pumps require fewer square feet of floor space than conventional pumps.

MAINTENANCE COSTS ARE REDUCED. Fluid-end, where most work is done, is at chest level. Bearing replacements are made without removing heavy crankshafts or connecting rods. Crossheads on all Direct Flow Pumps can be worked on or removed from pump without disturbing fluid-end.

TELL US ABOUT YOUR PUMPING PROBLEM. The chances are that one of our standard pumps — or a modification of one — will do your job. Detail your problem and we'll send you a copy of the Data Sheet that describes the Direct Flow Pump we recommend. Write to: The Aldrich Pump Company, 26 Pine Street, Allentown, Pa.



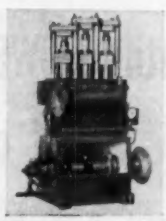
Aldrich inverted vertical pump design

...for your tough pumping problems specify ALDRICH

The entire line of Aldrich Direct Flow Pumps feature two outstanding design innovations—inverted vertical design and sectionalized fluid-ends. These two features have helped make Aldrich the organization hydraulic engineers turn to when they face tough pumping problems. If you have a pumping problem, turn it over to the men who have never turned down a challenge.

CHECK THESE ADVANTAGES OF INVERTED PUMP DESIGN:

Smaller Foundations
Simpler connection with prime mover
Less floor space required
Reduced maintenance costs



Write today for Data Sheets describing the Direct Flow Pump Series.

THE ALDRICH PUMP COMPANY

Originators of the Direct Flow Pump
30 PINE STREET
ALLENTOWN, PA.
Representatives in principal cities

MUD ACID

Versatile DOWELL treatment dissolves mud for fast clean-up of caked pay zones, choked formations

Getting drilling mud off the face of the pay, restoring formation permeability, opening mud-fouled screens and liners, freeing stuck drill pipe . . . these are jobs for Dowell Mud Acid. As a spearhead, to clean up the well ahead of fracturing and squeeze cementing operations, Mud Acid has proved particularly effective.

This Dowell treatment is specifically designed to dissolve clay minerals and to prevent the swelling of bentonitic materials. It will also dissolve any material soluble in hydrochloric acid, such as limestones and dolomites.

Special additives help minimize creation of emulsions. A Dowell inhibitor helps protect well equipment from acid corrosion, even at temperatures above 300°F.

Wherever and whenever clay, silicates or bentonitic materials are a problem call for Dowell's fast, effective Mud Acid.

For service, or for more information, call any of the 165 Dowell offices in the United States and Canada; in Venezuela, contact United Oilwell Service. Or write Dowell Incorporated, Tulsa 1, Oklahoma, Department K-15.

services for the oil industry

DOWELL

A SERVICE SUBSIDIARY OF THE DOW CHEMICAL COMPANY

FIELD CASE HISTORY

BIG MUDDY WATER FLOOD

R. W. HALLER | CONTINENTAL OIL CO.
GLENROCK, WYO.

Abstract

This paper presents a summary of the production and waterflood history of the Second Wall Creek Reservoir in the Big Muddy field. This highly successful Eastern Wyoming water flood has doubled the production from the Wall Creek in less than two years of operation. An outline of the laboratory and reservoir studies which culminated in the installation of a pilot water flood in 1953 is presented. Pertinent reservoir data, such as oil and water saturations, are given. The development program and current production practices of the waterflood program are also presented. The primary and waterflood performance is shown for several individual wells and for the entire flood. Cumulative waterflood recoveries and the estimated ultimate recoveries are given, in conjunction with the current development and operating costs and the future economics of the waterflood program.

Introduction

The Big Muddy oil field is located about 4 miles west of Glenrock in Converse County, Wyo. The field was discovered in 1916, although Wall Creek production was not encountered until 1917, when State 10 Lease Well No. 1 was brought in flowing at a rate of 150 BOPD. This discovery touched off a prolific drilling program and brought about one of Wyoming's famous oil booms.

Most of the wells drilled to the Wall Creek were located along the crest of the structure and were generally spaced on a 10-acre pattern as shown in Fig. 1. Full development of acreage did not take place on leases located on the flanks of the structure. However, lease line drilling was sufficient to prove up this peripheral area.

The majority of wells were drilled with cable tools to the top of the sand. Casing was then run and the wells tailed in to a depth 50 to 60 ft below the sand top. A typical casing program consists of 40 ft of 20 in. surface pipe, 250 ft of 15½ in. pipe to seal off a good water sand, 1,000 ft of 12½ in. pipe to seal off the Shannon Sand, 1,900 ft of 10 in. and 2,600 ft of 8¼ in. pipe to combat hole cavings, and finally 3,000 ft of 6¼ in. casing set on top of the sand. There is little record of cementing having been done in the early wells.

In all, a total of 214 wells were completed in the Second Wall Creek Sand. Of this total, 81 wells are still producing with the remainder having been plugged, shut-in, or converted to water injection wells. The average initial well potential was 350 BOPD. Subsequent deepening of these wells from 4 to 50 ft during their early productive life increased potentials to a maximum of 2,000 B/D. These results indicate the existence of a highly permeable zone in the middle of the Second Wall Creek Sand. A maximum Second Wall Creek field production of approximately 7,900 BOPD was reached in 1919. The production decline was rapid but was retarded to some extent by the completion of additional wells in 1926 and 1927. Initial potentials on these later wells were from 15 to 50 BOPD. These low potentials were due to completions in the depleted portions of the reservoir. The production history is shown on Fig. 2. The Midwest Refining Co.,

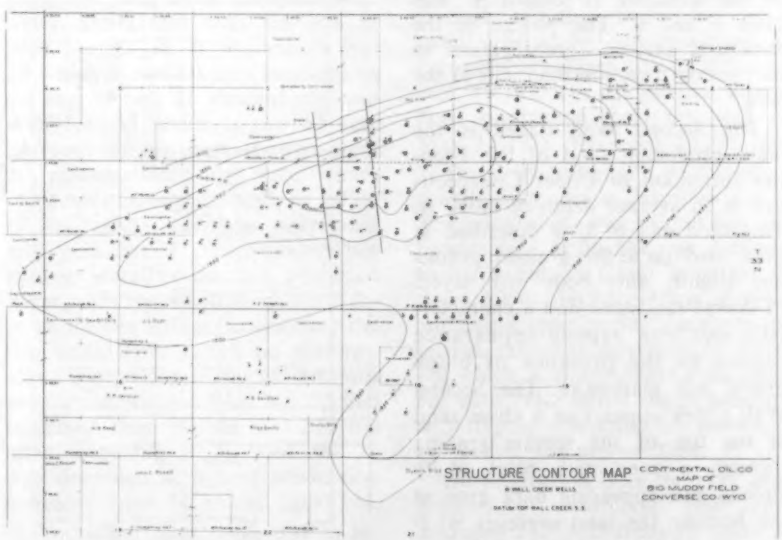


Fig. 1 — Structure contour map of Big Muddy field.

Paper presented at Joint Meeting of Rocky Mountain Petroleum Sections, AIME in Denver, May 26-27, 1955. Manuscript received in Petroleum Branch office on June 6, 1955.

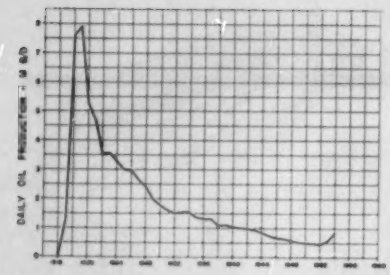


Fig. 2 — Second Wall Creek production in Big Muddy field.

The Ohio Oil Co. and The Texas Co. initially developed the Big Muddy field. Continental began acquiring leases in 1923 and currently owns about 98 per cent of the primary productive area of 3,270 acres. The data presented in this paper are based on Continental leases.

Central power units were utilized as a means of artificial lift on the majority of wells, although in some cases, individual pumping units were used. Due to the effect of the water flood, many of the wells are being converted from central power facilities to individual beam units.

Geology

The Big Muddy field is in the southwest corner of the Powder River Basin and at the northwest end of the Laramie Range. The structure has a closure of about 300 ft and is situated on an east-west trending anticlinal fold. The Pierre shale is exposed on the surface and beds in this formation exhibit dips of 2 to 10 degrees on all flanks except the north where dips of 20 degrees are in evidence on the surface. The high of the structure is located in Sections 8 and 9. The plunge of the structural axis is slightly greater in an easterly direction than it is to the west.

The Second Wall Creek is the main producing sand of the Frontier formation of Upper Cretaceous age at an average depth of 3,050 ft. This sand can best be described as gray, medium to fine grained, porous and slightly silty beds with layers of coarse sandstone and a characteristic salt and pepper appearance caused by the presence of black grains and glauconite. The Second Wall Creek appears as a clean sand at the top of the section grading through a zone with black shaly streaks and appearing dark gray at the bottom; the sand averages 90 ft in gross thickness.

During the years following the early development of the field various structural interpretations by contouring were made through data available from the wells that had been drilled in the field up to Sept., 1943. These old and not too accurate well data represented the only source of information on producing horizons and their positions in the holes drilled. In Sept., 1943, another drilling campaign of the deeper Dakota and Lakota Sands was initiated from which electric and radioactive logs were obtained. The isopachous map as shown on Fig. 3 was drawn from these data.

Reservoir Performance

The principle source of reservoir energy for the Second Wall Creek Sand was solution gas with a possible local water drive from the northeast flank. Initial reservoir pressure was about 1,320 psig. This declined to 50 psig or less prior to waterflooding as a result of the production of 22 million bbl of oil.

The daily production of gas in 1918 and 1919 was more than 4 million cu ft and decreased to about ½ million cu ft in 1936. At the present time, the gas production is too small to measure. Since these are the only data available, there are no accurate totals on actual gas production. The original GOR was estimated to be about 350 cu ft/bbl of stock tank oil.

Varying amounts of fresh water were produced from edge wells located on the north and northeast edges of the field. No disposal problem arose due to the nature of the produced fluid.

A gas injection program was started during 1935, but was abandoned shortly thereafter due to the apparent channeling to offset producing wells and the high purchase price of the gas. For the period that this program was utilized, the key well took 80 MMcf/D of gas at a line pressure of 300 psig, no compressor being necessary.

Waterflood Study

In view of the reservoir performance exhibited by the Second Wall Creek, it was concluded that the natural reservoir energy would recover 19 per cent of the pore space or 175 bbl/acre-ft. It was apparent that natural water encroachment would be so localized as to be of minor importance in increasing recovery. Furthermore, it was found that many leases in the field were approaching an uneconomical rate of production. The attitude of the management of the Continental Oil Co., when these data were presented, was that immediate effort should be made to develop a method of recovering the large reserve of oil remaining in the reservoir.

After considerable experiments and studies were performed, it was decided that a waterflood of the reservoir offered the most economical method of increasing oil recovery. It was believed that a controlled flood could duplicate or improve the recoveries as shown on the Barber Lease. The performance of this lease had indicated that a natural

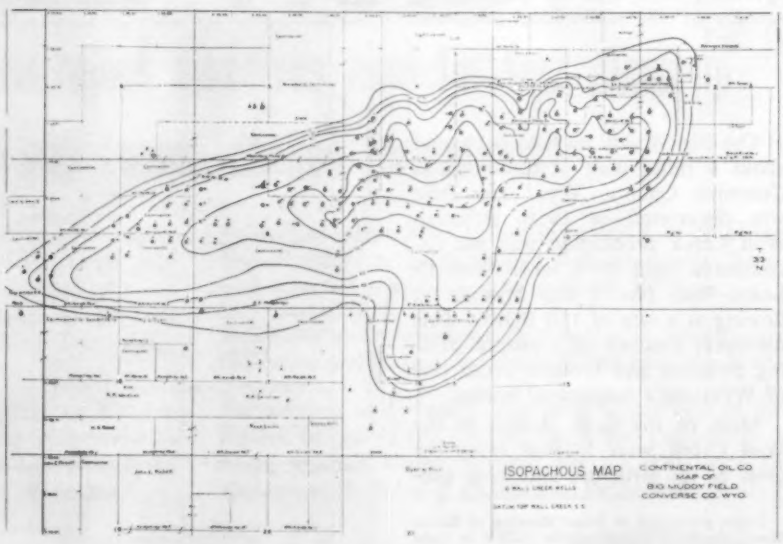


Fig. 3 — Isopachous map of Big Muddy field.

water drive was in effect in this area. A noticeable advance of a flood front with wells going to water and increased oil recovery of 76 bbl/acre-ft for the lease in general seemed to indicate that the productivity of the sand is not impaired in the presence of additional formation water.

It was, therefore, decided to initiate a small scale flood to determine whether water would displace oil from the Second Wall Creek and to obtain information and experience for the expansion of the flood if this method appeared successful.

Water Supply and Distribution

The most logical supply of water for injection purposes is the waste water produced from the Lakota zone of the Big Muddy field. Typical analyses of these two waters as shown in Table 1 indicates that the Lakota water is compatible with the interstitial water in the Second Wall Creek Sand. No chemical treatment of the water has been necessary since plugging of the sand face is not evidenced.

The primary source of Lakota formation water is produced with oil from two wells equipped with submersible centrifugal pumps. The oil and water are produced into two 6 ft x 10 ft water knockouts where fluid separation occurs. The water is then directed under pressure into a 10 ft x 20 ft precipitator where it is cleared of any oil film. Input water flows from the precipitator into a 4 in. header and thence into 2 in. lead lines where the water is metered before being injected down the casing. Input volumes are regulated by globe-type throttling valves on each well. All lead lines are buried although wellhead equipment is not insulated since the input water has a temperature of approximately 75 degrees. The water injection manifold is housed in conjunction with the accessory equipment on the precipitator.

TABLE 1—WATER ANALYSIS—BIG MUDDY FIELD

Formation	Lakota PPM	Second Wall Creek PPM
Total Solids	466	3,808
Specific Gravity at 60°F	1.012	1.000
PH	8.40	8.75
Chlorides	Nil	638
Sulfates	Nil	Nil
Carbonates	18	121
Bicarbonates	293	2240
Hydrogen Sulfides	Nil	Nil
Organic Acids	Nil	Nil
Sodium	155	1225
Potassium	Trace	15
Lithium	Nil	Nil
Magnesium	Nil	75
Calcium	Nil	Nil
Strontium	Nil	Nil
Iron	Nil	Less than 1
Aluminum Barium	Nil	Nil

Waterflood Performance

Several factors were considered in selecting a location for the pilot water flood. Primarily, if the flood did not succeed, the possibility of damage to the reservoir would be kept to a minimum. Secondly, in order to fully evaluate the effects of the flood, a location in which water encroachment was absent was considered desirable. As a third factor, it was also considered feasible to utilize leases which were approaching an uneconomical rate of production. As a final consideration, accessibility to sources of water supply were also investigated.

The location chosen is in the west central portion of the field as shown on Fig 4. The sand body in this location is approximately 90 ft thick, and the producing wells nearest to the injection wells were producing from 1 to 28 BOPD.

In March, 1953, a fresh water injection experiment was started in A. E. Humphrey Wells 21, 40, and 43 situated along the crest of the structure. These wells are located in a 1,280 ft x 1,280 ft x 750 ft triangle with A. E. Humphrey No. 41 as the center producing well. The paramount reason for establishing such an injection pattern was to determine any effect of the pilot water flood in a minimum amount of time.

During the first week of water injection into Well No. 21, its west offset, A. E. Humphrey No. 22, was tested and found to produce 3 bbl of oil and 64 bbl of water. In three days, the well went completely to water. Coincident with the loss of Well No. 22, A. E. Humphrey No. 18 which is two 10 acre locations to the east of No. 21 watered out, and Well No. 33 which is two 10 acre locations to the west showed signs of rejuvination. To trace water movement among the wells, a gallon of fluorescein dye was introduced into Well No. 21. Five hours later it was identified in the produced water from No. 22 suggesting a highly permeable stringer connecting the two wells. This waterflood performance was a repetition of previous production history. Well No. 22 had increased from 90 bbl to 1,226 bbl after deepening 10 ft. Well No. 21 was deepened 4 ft and production increased from 50 bbl to 2,000 bbl.

Production rates continued to increase on A. E. Humphrey No. 33 as shown on Fig 5 and reached a maximum of 128 BOPD and 9 BWPD in Aug., 1953. The well has experienced a normal decline since that time and is currently producing 28 BOPD and 119 BWPD. Total waterflood oil produced from Well No. 33 has been 51,257 bbl to May 1, 1955. The rapid stimulation of this well and the watering out of Wells No. 18 and 21 are unusual in the general waterflood performance.

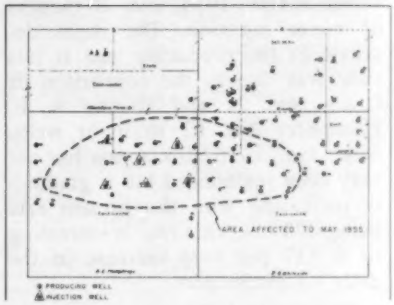


Fig. 4 — Pilot water flood, Second Wall Creek sand, Big Muddy field.

Minor oil production increases of from 10 to 20 BOPD were observed in a line of wells east of the input Well No. 21. For example, the effect of the water flood was noted in R. B. Whiteside No. 28, approximately 2,800 ft east of Well No. 21, at the same time that Key Well No. 41 was affected. The remaining producing wells to the north and east and the original injection area showed evidence of stimulation from nine to 12 months after injection operations were initiated.

Well No. 41, situated between input Wells 40 and 43, was producing 1 bbl of oil and 15 bbl of water prior to the pilot water flood as shown on Fig 6. Oil production steadily increased on this well after nine months of input operations and is currently averaging 110 BOPD and 109 BWPD. The cumulative waterflood production from this well to May 1, 1955, has been 44,595 bbl.

The daily waterflood performance for the pilot area is shown on Fig 7. The initial daily water input was approximately 5,500 bbl and declined to 1,025 bbl, as fill-up increased to Aug., 1954. With the completion of additional input wells, the daily injection rate was increased to 3,400 bbl which is approximately the present rate. The initial input pressure was 10 psig or less and has remained as such to the present time.

Oil production from the pilot area preceeding waterflood operations averaged 162 B/D from 19 wells. A production rate of 670 B/D was ob-

tained in Oct., 1954, after 20 months of water injection. The slight decrease in the producing rate at this time was due to the conversion of Crary Nos. 21 and 30 and A. E. Humphrey No. 62 to input wells. Since Jan., 1955, production has not only been maintained but is gradually increasing with the present rate being 870 bbl. This rate is increasing to a 537 per cent increase in the daily oil production.

Water production averaged approximately 100 bbl at the initiation of water injection operations. This rate has gradually increased until the present water production is approximately 1,320 bbl.

The cumulative waterflood performance curves, including produced water to produced oil ratios and injected water to produced oil ratios, are shown on Fig. 8. The cumulative oil production as a result of waterflood operations from March, 1953, to May 1, 1955, amounts to 351,967 bbl. With a cumulative water production of 389,964 bbl, the produced water to produced oil ratio is 1:1. A cumulative water input total of 1,564,413 bbl provides a cumulative water input to produced oil ratio of 4:1.

Thermometric and Spinner Surveys

In May, 1954, after injection operations had been maintained for over one year, thermometric and spinner surveys were obtained on the input wells. These wells were tested under input conditions only. The surveys made at injection well, A. E. Humphrey No. 43, are shown on Fig. 9. The spinner and thermometric survey results compare very favorable and indicate that the injected water is being displaced into the upper 40 per cent of the sand section.

Development and Operating Costs

To the present time, a total of $65,033 has been expended for the development of the water flood. Of this figure, $61,984 was capital investment, including 11 pumping units necessary to lift the increased production, and $3,049 was operating expenses directly attributed to the production of waterflood oil. For the 600 acres currently under flood, the development cost has been $108 per acre. This comparatively low expense is the result of a cheap water supply and the good mechanical conditions of surface and subsurface equipment.

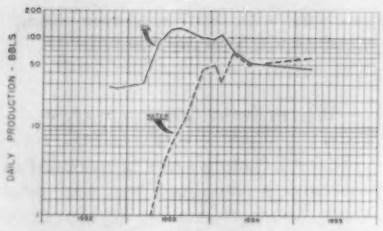


Fig. 5—Individual well performance, A. E. Humphrey Lease, Well No. 33.

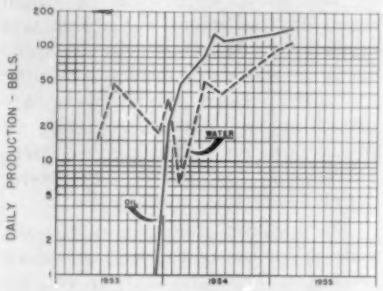


Fig. 6—Individual well performance, A. E. Humphrey Lease, Well No. 41.

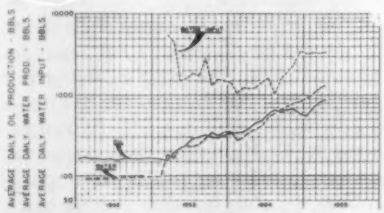


Fig. 7 — Pilot flood performance.

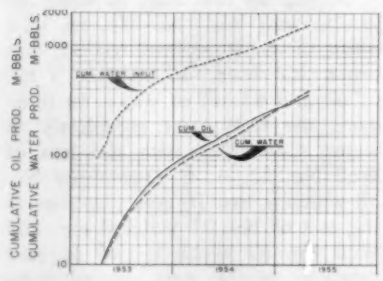


Fig. 8 — Pilot flood cumulative data.

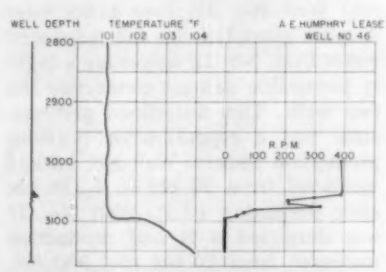


Fig. 9 — Spinner and thermometric surveys.

A slight decrease in operating costs has been noted during the waterflood life. At the beginning of the flooding program, the cost was 43 cents/gross bbl. Present rates under flood operations have been 38 cents/gross bbl although the current trend indicates that the lifting cost will be even lower. This reduction in cost was a result of the low development investment and the excellent recoveries obtained to date.

Future Expansion of Flooding Operations

Expansion of waterflood operations to include the entire reservoir is now underway in view of the success of the present limited flooding program. The expansion will necessarily entail the drilling of additional water and producing wells. This development and the conversion of present inactive wells will increase the input and producing wells for the reservoir to a total of 106 wells.

Acknowledgment

The author expresses his appreciation to the Continental Oil Co. for permission to publish the data and to John W. Tynan, R. C. Bartels, and W. P. Schmoe for their assistance in the preparation of the manuscript.

Appendix

Crude Characteristics

An analysis of gas free crude from the Second Wall Creek Reservoir indicates:

Specific gravity	0.846
API gravity	35.80°
Saybolt Universal Viscosity @ 100° F	47 sec.

The viscosity of the gas free crude is calculated to be 5.9 cp at the reservoir temperature of 100° F. The viscosity of gas saturated crude at the reservoir temperature and pressure is estimated to be 3.5 cp. The average viscosity of the reservoir oil is estimated to fall within this range of values.

Reservoir Characteristics

The average reservoir characteristics, as determined by the calculation of production data and evaluation of cores, were as follows:

Porosity, per cent	19.2
Permeability, md	20.5
Connate water, per cent	25.5
Residual oil saturation, per cent	55.3
Waterflood residual oil saturation, per cent	30.
Average sand thickness, ft	42.

★★★

REPORT of OPERATIONS, 1945 THROUGH 1954, NAVAL PETROLEUM RESERVE NO. 1, ELK HILLS

F. W. GOOCH, JR. — COMMANDER, UNITED STATES NAVY
R. H. ADAMS, MEMBER AIME — STANDARD OIL CO. OF CALIFORNIA, TUPMAN, CALIF.

Abstract

This paper presents the progress of operations within the Elk Hills field for the period 1945 to 1954. Since World War II and the subsequent shut-in of this field, many projects were initiated to determine the best method of protecting the various reservoirs. All of the Shallow Oil Zone programs were predicated around a reservoir which was in a state of pressure unbalance caused by heavy withdrawals of fluid in relatively short periods of time. The basic studies centered around: the use of gas injection, evaluation of an unrestricted water encroachment and its opposite heavy downdip withdrawals to utilize gravitational drainage, general studies of movement of reservoir fluids, and the protection of surface equipment. These programs have been changed from time to time, depending upon results obtained. Some of the results are unique. Currently the programs involve controlling encroachment through production from invaded areas and remedial measures to stop or minimize the downdip migration of oil. A primary objective of all programs is to maintain the Reserve in a state of readiness whereby it will be able to produce oil in substantial quantities whenever the strategic situation of the United States so requires.

An active drilling program has resulted in further development of the Shallow Oil Zone, the exploration and development of the Stevens Zone, and adding a new and as yet untested pool, the Carneros.

Paper presented at Pacific Petroleum Chapter Fall Meeting in Los Angeles, Oct. 7-8, 1954. Original manuscript received in Petroleum Branch office in Aug., 1954. Revised manuscript received on Sept. 30, 1955.

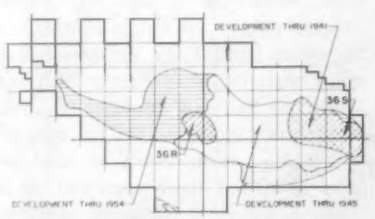
The opinion or conclusions contained herein are essentially those of the writers and are not to be construed as official or reflecting the views of the Dept. of the Navy, The Unit Operation, or the Standard Oil Co. of California.

History and Stratigraphy

This paper is intended to supplement an original technical publication titled "Experimental Production Projects and Exploratory Drilling at Elk Hills" by M. C. Eastman and F. L. Ruhlman, which was presented at the Petroleum Branch, AIME, Fall Meeting of 1947. It will report the progress of operations made since January of that year.

Since Elk Hills was first discovered in 1919, when Well Hay No. 1 in Section 36R was placed on production, it has been marked by erratic development of its resources. Only during the past 10 years has the potential of this great field been developed to a point of probably having, at this time, the largest capacity to produce of any single field in the State of California.

In Jan., 1920, Well No. 1-36S, located 6 miles east of the discovery well, was completed flowing in excess of 5,000 B/D. Drilling in this area proceeded rapidly such that by early 1929 over 200 wells were producing. The relationship of Section 36R and Section 36S is shown on Map 1. For the following 15 years little drilling was scheduled.



Map 1 — Elk Hills Shallow Zone development.

In June, 1944, in order to provide additional crude oil, the 78th Congress authorized the development of the Reserve to increase production from its then existing level of 15,000 B/D to 65,000 B/D. Within eight months production reached the directed limit and remained at this rate of withdrawal until the cessation of hostilities in Aug., 1945. During this 15 months of accelerated activity 317 wells were drilled, four of which were abandoned. The field capacity was increased to about 71,000 B/D. During the period of June, 1944, to Aug., 1945, over 15 million bbl of oil, 5,500 MMcf of gas and 2 million gal of gasoline were produced. Practically all of this production was taken from the Shallow Oil Zone. A small amount was produced from the Stevens Zone which was discovered in 1941 and had five producing wells during this period.

At this time it was clear that the field could support additional development. However, as the exigencies of war had been satisfied, a Navy directive was issued that reduced withdrawals to the original 15,000 B/D. In May, 1946, the Navy directed that production should be reduced to that amount required to protect the reserve on the Elk Hills structure. A ceiling of

7,950 B/D was set, as it was thought that this withdrawal would be adequate to protect the various pools within the reserve from damage and assure a continued state of readiness for maximum production in case of national emergency. With this reduction only a few of the Shallow Oil Zone wells remained on production.

The known stratigraphic column at Elk Hills extends from the Pleistocene to the Lower Miocene. A diagrammatic stratigraphic section is shown in the composite electric log, Fig. 1.

Shallow Oil Zone

General

The Shallow Zone is defined in the Unit Plan Contract as being "All oil and gas bearing formations of Pliocene age above the Reef Ridge shale, except the Dry Gas bearing formations above the top of the Lower Scalez Marker bed." It consists of a series of interbedded shales and sands of variable characteristics. The structure which is shown on Map 2 is anticlinal, trending nearly east-west with several closed highs and an oil closure of about 1,500 ft. Faulting is common in the eastern portion, and in general there is a striking similarity between surface topography and the subsurface structure. These faults for the most part are of normal type dipping 45 to 90 degrees with displacements up to 250 ft. It is notable that only a small part of the entire faulting system appears to offer any resistance to the flow of fluids across their plane. This fact has been substantiated by a wealth of depth pressure measurements, observing the movement of injected gas by using helium as a tracer, production data, and water encroachment history. The degree of faulting is less in the western portion of the structure; however, it is possible that a more complex faulting system is present but has not been detected with the existing well density.

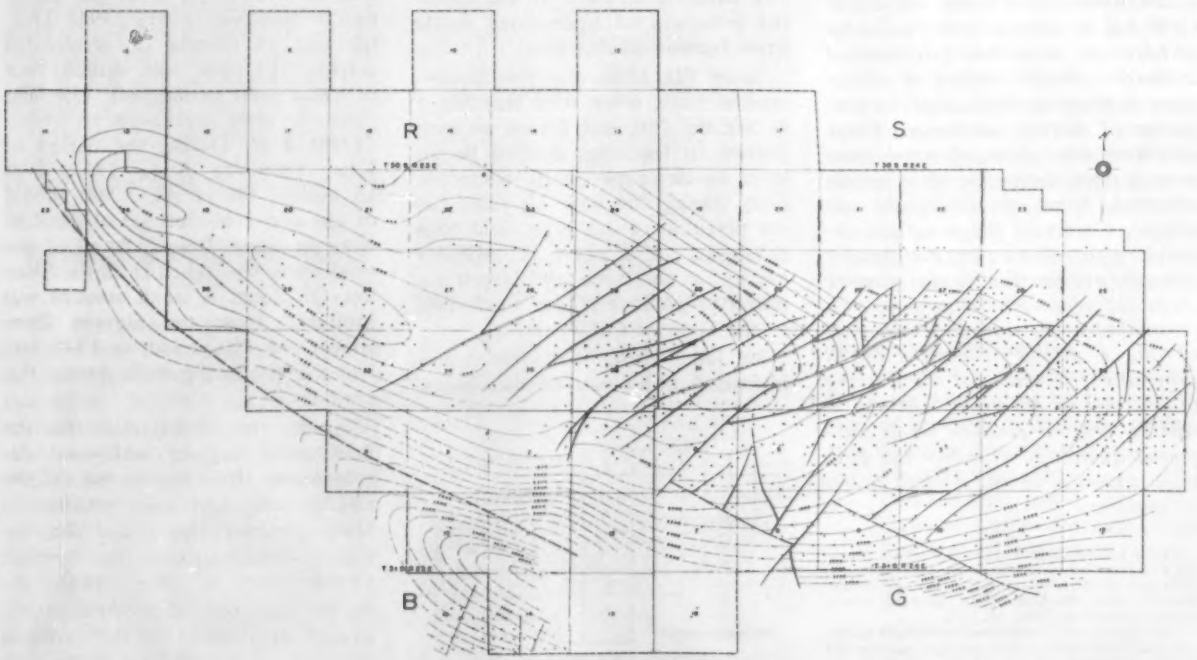
Within the Shallow Oil Zone the San Joaquin Clays and Etchegoin formations are represented. The oil productive measures of the Shallow Oil Zone occur from 50 ft above to 600 ft below the Scalez marker and vary in drilled depth from 2,000 to 3,500 ft. In general, it may be stated that sand distribution within Elk Hills is such that the younger sands are present and productive in the eastern portion of the field; they pinch out in a westerly direction and the older sediments become productive. This is demonstrated in part by the pinchout of the SS-1 sand and the merging of the SS-2 and M into one sand section along the western boundary of Section 33S. An indication of capacity may be obtained from the generalized sand characteristics in Table 1.

An exploratory drilling program was commenced in July, 1945, to delineate the productive area of the various Shallow Zone Sands and to assist in planning for future development of the Shallow Oil Zone. Prior to the exploratory program only the eastern half of the field had been developed. Little was known about the western portion, except that the younger productive sand bodies thinned from east to west and appeared to pinch out in the center of the field. The principal sands in this group were the SS-1, SS-2 and the Mulinia. The Sub-Mulinia was a thin sand that was fairly continuous in the eastern portion of the field. It was found to extend well into the western portion in an irregular fashion. In the western portion of the field the Bittium sand occurs as a series of thin lenticular sands that are both oil and gas productive at the higher structural position, while the Wilhelm Sands are silty sands with irregular oil and gas productive areas occurring where there is sufficient permeability.

Following the exploratory drilling, the third major development program was started in May, 1951. Un-

TABLE 1 — SAND CHARACTERISTICS

	Max. Thickness	Avg. Thickness	Avg. Porosity	Permeability Md
Above Scalez (AS)	25	10	38.2	2,000
First Sub-Scalez (SS-1)	99	46	34.0	2,100
Second Sub-Scalez (SS-2)	45	18	34.6	1,600
Mulinia (M)	36	23	35.4	2,400
Second Sub-Scalez and Mulinia (SS-2 & M)	51	20	34.4	1,700
Sub-Mulinia (SM)	22	8	33.4	700
Bittium (B)	9	3	36.4	750
High Productivity Wilhelm (HPW)	16	7	32.1	200
Low Productivity Wilhelm (LPW)	32	16	31.7	75



Map 2—Shallow Zone structure map.

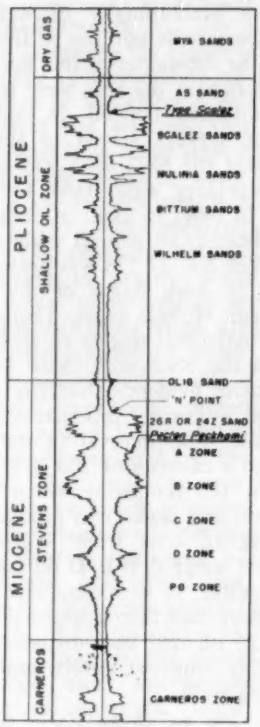


Fig. 1 — Generalized stratigraphic section.

der this program the better locations in all of the Shallow Zone Sands were to be drilled. This has resulted in drilling 145 wells with a few locations remaining undrilled at this time.

In order to examine the sequence of events contributing towards reservoir pressure unbalance, it will assist to review the volume of withdrawals taken during various time periods. The initial development in and around Section 36R (Hay Carman Area) resulted during the period 1919 to 1932 in withdrawing about 6½ million bbl of oil and an unknown large volume of gas. All wells within this area had been shut in by 1932. Six miles east in the Section 36S area, which was discovered in 1920, production was large, and by late 1942 about 153 million bbl of oil had been produced. Therefore, production resulting from the first stage of development in the Shallow Oil Zone was about 160 million bbl of oil and large volumes of gas and water at widely separated locations.

The second stage of development (1942-1945) during World War II is outlined on Map 1. Twenty-seven million bbl of oil and 7 billion cu ft of gas were produced during this period.

Thus, upon conclusion of two major stages of development at various time periods, approximately 187 million bbl or about one-third of the estimated recoverable oil had been produced. Fig. 2 is a chart showing the production from the Shallow Oil Zone. This briefly summarizes the development and production history for the period 1919-1945.

Readiness Program

The wartime development had confirmed the fact that the eastern part of the Shallow Oil Zone was generally pressure depleted except for a few separate areas. The heavy withdrawals during this period had resulted in an unbalanced pressure distribution in all areas. In addition to this unbalanced pressure distribution, production late in 1945 was curtailed from 65,000 B/D to 15,000 B/D and would in the future probably be reduced even further.

Based on this information the Operating Committee[1] recommended and the Engineering Committee concurred with a program that was designed to fulfill the obligations of the Unit Plan Contract to: (1) conserve as much oil, gas, gasoline, and associated hydrocarbons in the ground as possible; (2) maintain the Reserve in a condition of readiness whereby it will be able promptly to produce oil in substantial quantities whenever the strategic situation of the United States so requires; and (3) insure the maximum ultimate recovery of oil, gas, natural gasoline, and associated hydrocarbons.

Seven projects or study areas were selected to develop information that would lead to maintaining the reserve in good oil field condition but in an essentially "shut-in" condition.

Protection of Surface Equipment

A program for the preservation, inspection, and storage of all inoperative surface equipment, needed for operation of the Reserve, was developed in accordance with accepted Armed Forces and industry procedures. Its detail was outlined by Ruhlman and Eastman.[1]

During the past eight years at various times and under different periods of shut-in, the individual units, pumps, engines, and valves have been disassembled to visually inspect and determine the effectiveness of this program. Results to date have been satisfactory in that in every instance of disassembly, corrosion has been at a minimum and nearly all of the equipment has been in a workable condition.

[1]Reference at end of paper.

Gas Injection Project

In the newly developed area of the Shallow Oil Zone during World War II, the heavy withdrawals of crude had reduced the reservoir datum (2,000 ft SS) pressure from an estimated 850 psi to about 600 psi. It was possible to return only a portion of the gas produced during the war period to the reservoir as a conservation measure because of the lack of compression facilities. In an attempt to retard encroaching edgewater from the north and improve future productivity, a full scale gas injection project was initiated into the SS-2 and M sands in the latter part of 1945. As previously reported[1], the first part of the program appeared to offer a reasonable chance for success, but as injection proceeded the following was noted by 1950.

1. The expansion of the gas envelope was highly irregular with gas channeling through the more permeable portions of several sands. It was believed that any well having a GOR in excess of 1,000 cu ft/bbl could be considered to have been captured at least in part by injected gas. (Normal produced GOR's in this area were about 125 cu ft/bbl).

2. An extensive tracer study, in which two waves of helium-laden gas were injected at a concentration of 0.1 per cent by volume, had conclusively substantiated excessive channeling and had allowed a fair prediction of future gas cap movements.

3. Areal reservoir pressures remained in a state of unbalance.

In view of the irregular movement of gas, the injected volumes were materially reduced and certain additional injection locations selected.

By June, 1952, the following data were available:

1. The project had failed to stop encroaching edgewater from the north.

2. Crestal pressures had increased to a point that adverse pressure gradients existed towards the south in the SS-2 and M sands. These gra-

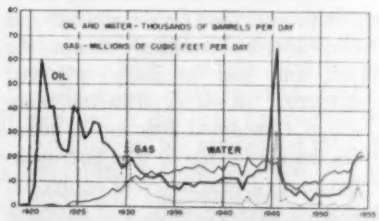


Fig. 2—Shallow Oil Zone production.

dients were of sufficient magnitude to cause reservoir fluids to move downdip into water bearing sands.

3. This rate of downdip fluid movement was computed to be about 2 million bbl/year.

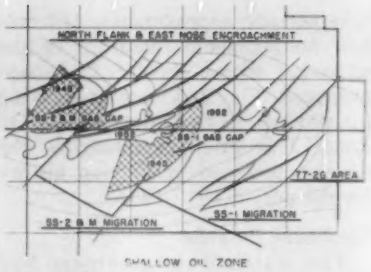
4. Injected gas moving easterly into Section 4G was migrating through wells dually completed in the zone of injection (SS-2 and M) and the SS-1 sand of lower pressure. In addition gas was moving erratically across a complicated system of faults. Pressure, production and helium analyses of gas from crestal portions of the SS-1 sand substantiated that migration of the injected gas into the lower pressured zone was occurring in quantity.

The project was terminated in June, 1952, because of the probability that: (1) further injection would only serve to create a greater unbalance of reservoir pressure, (2) it now appeared impossible to confine gas to its zone of injection, and (3) of no lesser importance, further injection would probably increase the losses in ultimate recovery on the south flank in the SS-2 and M and SS-1 sands. The extent of the gas caps at this time is shown on Map 3. Continuation of this program is discussed later in the report as a separate part of the modified State of Readiness Program.

In addition to the main area of gas injection, two unsuccessful attempts were made to control advancing edgewater:

1. One attempt, in and adjacent to Well No. 88-28S, was started in Sept., 1950, in one particular fault block on the north flank. Injection continued until May, 1951. The results of production testing, depth pressure surveys, and correlation work from geologic structure sections indicated that: (a) no pressure increase was observed at any locations downstructure to the north of the injection location; (b) pressures had increased to the south and upstructure outside the injection fault block; and (c) GORs had increased somewhat upstructure towards the south.

It was concluded, because of an incompetent fault system, that gas could not be confined within the block and had probably migrated upstructure to merge with the main gas cap. Continued injection in quantities then indicated to stop encroachment may have resulted in additional losses of producibility and ultimate recovery.



Map 3 — Shallow Oil Zone gas cap and project area map.

2. Another, the 77-2G project, was located at the east end of the south flank, where a rapid and damaging movement of water had been observed in the SS-2 sand. Injection commenced in Oct., 1950, and was stopped in Feb., 1952. At that time it was concluded that injection of gas into Well No. 77-2G was not arresting the advance of SS-2 edgewater; in addition, oil was being driven downdip into water sands in undeveloped areas.

Major Water Encroachment Study

The encroachment of water is not a new problem in the Shallow Oil Zone. It started in quantity in the early 1920's. During the period 1920 to 1945, where advancing edgewater was prevalent, it had been produced in order to provide an efficient control for the production of upstructure oil. At the close of World War II it became necessary to determine as expeditiously as possible whether an efficient sweep would result if water was allowed to advance into the shut-in reservoir and assist in repressuring, or whether this water would move preferentially through the more permeable portions of sands, thus leaving quantities of bypassed oil and serving only to impair the oil productivity in flooded areas.

An area essentially isolated by faults was selected for the Major Water Encroachment Study. The program commenced by shutting in 26 downstructure highly water productive wells. Water cuts in most of this area had been in excess of 90 per cent for several years. Five upstructure test wells were selected to produce continuously to measure any change in productivity which might be reflected. During the following two years there was a large increase in pressure. Subsequent volumetric calculations indicated the movement of water upstructure was too rapid to effectively flush the sands in the area under study. Water witch surveys showed that the water was advancing preferentially through the more permeable portions of the SS-1 sand; the remainder of this sand and other sands in the area were not being uniformly flooded. In addition, spinner surveys served to substantiate that the SS-2 sand was receiving migratory water from the SS-1 sand. In order to assist in evaluating the efficiency of natural water flooding, Well No. 77-27S was drilled and tested in each finger of the SS-1, SS-2 and Mulinia sands. There were eight individual fingers of sand tested. In the SS-2 sand there was no conclusive evidence that any major portion was water productive. Actually one sand interval in the SS-2 showed a capacity of 100 B/D clean oil. In the remaining seven intervals, oil and water was produced in varying amounts from 5 B/D oil with no water to 0 B/D oil and 226 B/D water. It was concluded from the above data that substantial quantities of oil had been bypassed and probably rendered unrecoverable by existing wells.

In view of these data, the 26 downstructure wells were returned to production at their prior identical operating rates. Before being shut in these wells had produced about 1,000 B/D oil and 5,500 B/D water. In April, 1948, four months after being returned to production, their withdrawals were 350 to 400 B/D oil and 5,300 B/D water. Thus the capacity of the wells that were shut in for two years was only about 40 per cent of their capacity in 1945.

The productive capacity of all wells in the area was about 2,100 B/D oil and 5,600 B/D water prior to the shut-in. During the subsequent two year shut-in period it was calculated that the production from the five observation wells should have decreased the areal productive capacity to about 1,850 B/D. However, upon returning the entire area to production at its prior identical operating rate, oil production had decreased to about 750 B/D. This was 41 per cent of the anticipated capacity. Subsequently gross withdrawals were increased about 30 per cent and part of the formerly wet area has cleaned up. Based upon identical gross withdrawals, the present productive capacity of the 26 downstructure wells is 46 per cent of the 1945 rate. This appears to confirm the previous conclusions that oil was bypassed and rendered unrecoverable, and that uncontrolled natural water encroachment is not an efficient displacing mechanism.

Dewatering and Gravitational Drainage Project

To determine the effects of gravity drainage as a producing mechanism, an area at the extreme east end of the field was selected. This area is separated from other areas by faults, so that the effects of water production could be localized. It was planned to reduce the pressure, and establish a downdip datum gradient favorable to gravity drainage, by maximum withdrawal of water and oil downstructure in an area which had been invaded by water.

Excessive sand trouble and mechanical conditions prevented the withdrawals of a sufficient volume of oil and water to have the desired effect. The conclusion was reached that the necessary reduction of reservoir pressure could not be achieved with existing wells and equipment. Since the area could not be dewatered, the gravitational drainage aspects of the project were not attained. However, this operation has retarded water encroachment into the clean oil sands.

Rotating Production Test Program

To accomplish the objective of providing continuing information as to each well's mechanical condition and productive capacity, a periodic production program was set up to test wells not produced under other programs. The results of this program has been very satisfactory. It has provided information to indicate the movement of water into oil sands and oil into water sands. It has also provided information on the effects of gas injection including the movement of gas into oil sands. In addition, it has periodically checked the mechanical condition of idle wells and facilities pertinent to their production. From these and other data a good operating rate for the Shallow Oil Zone has been estimated should it be called upon in the future to produce.

Protective Production of Wet Wells Project

The Protective Production of Wet Wells Project was developed to observe wells making appreciable quantities of water and which were not included in other projects. These wells were kept on continuous production in order to eliminate the possibility of loss in producibility and ultimate recovery through the irregular flooding of oil bearing sands by encroaching water.

The original program started with 58 wet wells producing continuously. Most of these wells were completed in more than one sand, or were open to a sand which has several separate lenses—one or more of these lenses being water-productive. The wells were produced to protect the reservoir by retarding the advance of edgewater into upstructure clean oil sands and to prevent water migration into clean oil sands through the wellbore. When wells on test under the Rotating Production Test Project were found to be water-productive, they were added to the Protective Production of Wet Wells Project for a sufficient period to verify the test production. If the wells remained water-productive, and were located so that water movement could cause damage, they were added permanently to the latter program.

Repair and Remedial Work Project

Many wells in Elk Hills were old wells that had been completed with inferior casing and methods as compared with modern standards. In addition, other wells were completed with more than one sand open and there was migration of fluids between zones or in some cases one sand was wet and of higher pressure while the others were clean. Since the purpose of the Repair and Remedial Program was to maintain all wells in the best possible condition for prompt availability of production and to prevent damage to the reservoirs, an intensive repair program was carried on from 1946 to 1949. Since that time only occasional repair work has been required under this program.

Modification of Readiness Programs

By 1952 data accumulated and analyzed furnished evidence that the original Readiness Program, which had been in effect for seven years, had not corrected the unbalanced reservoir pressure distribution and the irregular encroachment of water had not been controlled.

In addition, there was evidence that the unbalanced pressures on the south flank were causing downdip movement of oil into the aquifer in both the SS-1 and the SS-2 and M sands. In the SS-1 sand, as early as 1946, there was a gradual reduction of pressure in wells along the south flank and theoretical calculations using the datum pressure gradient indicated migration of oil downdip to the south. Since production had been negligible from the south flank of Elk Hills, the pressure decline and the downdip datum pressure gradient could only be explained by the recession of edgewater and an accompanying migration of oil into water sands. In the SS-2 and M sands it appeared, that prior to gas injection into these sands, there was a normal pressure gradient on the south flank with no evidence of a recession of the edgewater. However, with gas injection into these sands and the corresponding increase in crestal pressures, an adverse datum pressure gradient was developed which indicated there was movement of oil downdip into water sands.

Based on the above information in June, 1953, the Readiness Program was modified by terminating the Gas Injection Project, absorbing the Major Water Encroachment and Dewatering and Gravitational Drainage projects into a new project known as the North Flank and East Nose Water Encroachment Project and instituting three new projects. One project was the 77-2G Water Encroachment Study; the other two were the SS-1 South Flank Migration and the SS-2 and M South Flank Migration programs. The purpose of the last two projects was in general to prevent the loss in ultimate recovery due to the movement of oil into water sands. Map 3 illustrates the relative location of these new projects.

North Flank and East Nose Water Encroachment Project

The existence of an active water drive on the north flank and east nose of the Shallow Oil Zone had been recognized for many years, and in general was controlled in most areas. It was not until the latter part of 1945 when the field was returned to a reserve status that the rate of invasion became critical. As previously discussed, several projects were carried out under the Readiness Program to determine the effects of uncontrolled water encroachment. The results of these projects indicated that uncontrolled encroaching water bypassed large quantities of oil and rendered it unrecoverable. This was probably caused by a high permeability variation which permits excessive fingering of the encroaching water. In addition the large difference in pressures between different sands caused water to migrate from high pressure water sands into low pressure clean oil sands, through wells completed in more than one sand or across incompetent faults where a high pressure sand lies opposite a low pressure sand. Past experience at Elk Hills has proved that shutting in of production and repressuring by gas injection, has not prevented encroachment of water on the north flank and east nose.

Maps 4 and 5 show the area of edgewater encroachment in the SS-1 sand and the SS-2 and M sands which are the major sands of the Shallow Oil Zone where encroachment has taken place.

In 1952, in order to make a detailed study of the water encroachment problem, the north flank and east nose was arbitrarily divided into 12 areas with faults as the boundaries as shown on Maps 4 and 5. Calculations were then made to determine the rate of water invasion and influx in each of the sands and fault blocks. The calculated rate of influx was 34,860 B/D. Average gross production at this time was 19,160 B/D which indicated that influx exceeded withdraws by 15,700 B/D. These calculations excluded the SS-2 sand in fault block No. 12 as it was to be included in another project area. With the calculated rate of influx as a basis, a program was prepared that was designed to prevent any further movement of water upstructure and hold it at its then present position in any particular fault block. This was to be accomplished by withdrawing fluid from the invaded area at a rate at least equal to the computed rate of influx. The finalized program proposed that the production rates of wells then on production were to be increased to the maximum practical consistent with existing equipment, 27 shut-in wells located in the area of invasion were to be placed on continuous production, and additional wells as required were to be drilled and produced in the area of invasion. Additional data to aid in controlling this program were to be obtained by testing 48 wells one location upstructure of the 10 per cent water cut line. Depth pressure measurements were to be made at least every six months in the continuously producing wells and quarterly in the test wells.

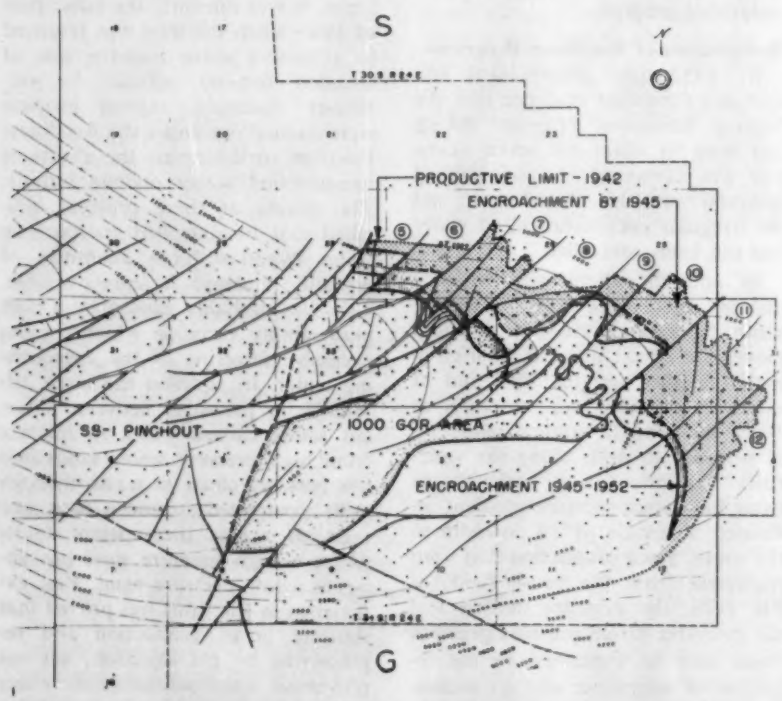
This program was initiated in June, 1953, and 28 wells have been drilled in the invaded area. It is estimated at this time that two more wells will be required. Present pressure and production data indicate that within the 21 sand areas of the 12 fault blocks considered, water encroachment is now controlled in all but eight sand areas. When drilling is complete, only six areas of the original 21 will be producing at a rate less than the computed influx. Additional time and continuing re-evaluation of the program will be required to determine whether additional drilling or other modification of withdrawal rate is necessary in order to control the remaining zones.

SS-2 Zone Water Encroachment 77-2G Area

Since 1945, when the Shallow Oil Zone production was reduced, the SS-2 wells located in Section 1G south of the fault running from 63-10G to 4D-1G had been characterized by increasing bottom-hole pressures and water production. In 1947 and 1948, most northeast downstructure SS-2 wells were plugged in an effort to eliminate bottom-hole water. The main effect of this remedial work was to reduce the productivity of the wells concerned. Reservoir pressures at this time were increasing at a rate of about 75 psi/year while essentially no fluid was being withdrawn from upstructure locations.

It was evident by 1949 that edgewater was invading clean upstructure sands. It was also noted that a secondary gas cap was present in the SS-2 sand in the vicinity of Well No. 77-2G. It appeared in this area that the SS-2 formed a separate reservoir, bounded on the north by a normal fault with a maximum displacement of about 200 ft. Therefore, in an attempt to arrest the rapid advance of edgewater, gas injection into upstructure Well 77-2G was initiated in Oct., 1950. The injection of gas was continued until Feb., 1952, at which time the following conclusions were made: SS-2 waters were continuing to advance; the expanding gas envelope was capturing clean oil wells and reducing productive capacity; oil was being driven downdip into water sands in undeveloped areas; and the northerly faulted limit of the area was pressure tight. In view of these data injection was discontinued and a study made to determine the corrective measures necessary to minimize probable losses in producibility and ultimate recovery being caused by continued encroachment from the northeast. As a result of this study a program was initiated in June, 1953, where all SS-2 wells in the area were placed on continuous production. The high GOR wells were placed on production within proper limits of control. In addition, three new downstructure wells to the northeast were drilled to permit sufficient withdrawals to retard the advance of edgewater.

In effect the recommended program was one of controlled water encroachment. Its purpose was to obtain the maximum ultimate recovery of oil, as all other means of controlling the area had failed and had resulted in reducing productive capacity. Static depth pressure measurements are obtained every six months and indications are that pressure gradients to the southwest have been reduced to where there is little evidence of oil being driven into water sands at this time. It also ap-



Map 4 — SS-1 water encroachment.

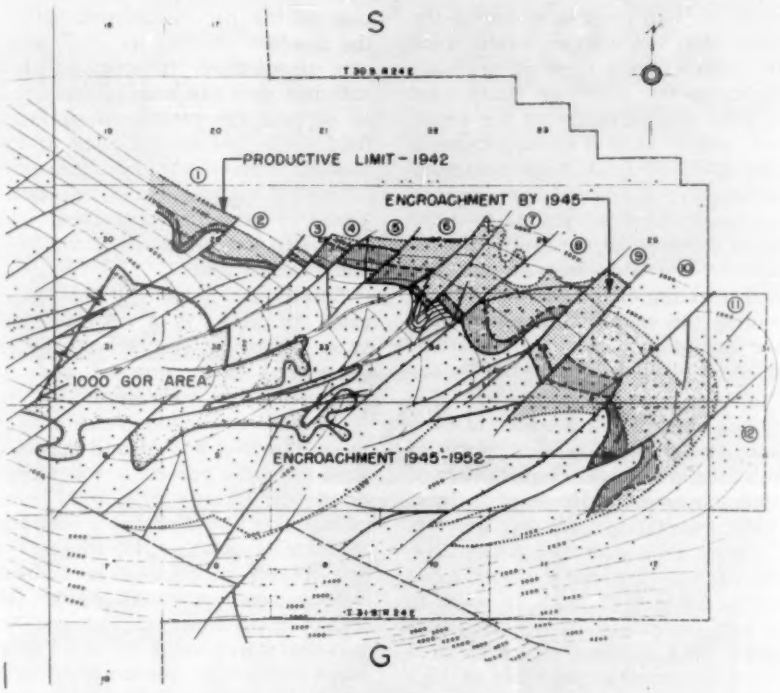
pears that fluid withdrawals to the northeast are controlling the encroachment of edgewater.

SS-1 South Flank Migration Project

As early as 1946 there was evidence of a large pressure difference in the SS-1 sand between the north flank and the south flank. On the north flank, downstructure pressures were greater than pressures at higher structural positions. The pressure unbalance on the north flank was accompanied by an influx of edgewater. On the south flank, downstructure pressures were less than pressures at higher structural positions which indicated a movement of reservoir fluids downdip to the south in the SS-1 sand. Since there were few wells on the south flank, it appeared possible that the indicated datum pressure gradients might not present a true picture of fluid movement in the reservoir. Exploratory drilling in 1946 and 1947 and development wells drilled in 1951 and 1952 showed the SS-1 sand was of very low pressure and confirmed the trend of lower datum pressure at the lower structural positions. In addition, pressures were continuing to decrease with time. Since there had been no appreciable production in this area, the only explanation was that the oil-water contact was receding, thus permitting the oil to migrate downstructure into water sands. Using Darcy's law, it was estimated that the rate of oil migration in Dec., 1951, was approximately 3,800 B/D.

By 1952, pressure measurements in SS-1 wells along the south flank showed that the bottom-hole pressure of all wells near the oil-water contact continued to decrease despite the absence of production. Several wells, whose initial production was mostly water, had with time started to produce oil in varying amounts. One of these wells, No. 77-9G, originally produced up to 300 B/D of water and 2 B/D oil; one year later it was producing about 100 B/D oil and 55 B/D water. At this time there is not an adequate explanation as to the cause of the adverse datum gradients and the resultant migration.

Based on the foregoing observations, it was concluded that oil was migrating downstructure into water sands and substantial losses of ultimate recovery were occurring. With only a limited knowledge of the aquifer, it appeared that there were two methods of retarding or stopping the movement of oil into edgewater



Map 5 — SS-2 water encroachment.

sands in order to minimize or prevent any further loss in ultimate recovery. One method, which was most desirable from the viewpoint of retaining a maximum amount of oil in the ground, was the injection of water into the aquifer near the oil-water transition zone. This water would be injected in a pattern and at a rate so that the oil-water contact would remain stationary in its present position along the south flank. Since the aquifer was known to be of large areal extent, although its exact extent and location of its boundaries are unknown, it did not appear feasible to attempt to raise the pressure of the entire aquifer. Thus the injection program would be designed to build up and sustain the edgewater pressures at a level where there would be no movement in the oil band. This of course would be a continuing program and would be required as long as the Shallow Oil Zone remained shut in. The other method was to produce certain downstructure wells at a rate sufficient to capture most of the oil moving downstructure before it migrated into water sands.

In view of the paucity of available data to determine the feasibility of water injection and the initial and continuing cost of such a project, a new program was initiated in June, 1953. This program placed downstructure wells on production, and the pressures in the two adjacent SS-1 sand gas caps were to be reduced by producing existing high GOR wells.

Subsequent to placing this program into effect, it was decided to study the feasibility of a water injection program and to evaluate the efficiency of the current production program by means of a laboratory project utilizing potentiometric and resistance capacitance models. It is expected that the study will be completed late in 1955.

At the present time theoretical calculations show that the rate of production in all areas except two exceeds the computed rate of migration. It is recognized that in all areas the movement of fluid past the last line of wells into water sands has only been minimized and not stopped, since datum pressures in the aquifer are lower than the pressures within the oil band.

SS-2 and M South Flank Migration

By 1945, production data from SS-2 and M wells on the south flank established that the edgewater in these sands was encroaching. Gas injection was started in the latter part of 1945 in an attempt to restore reservoir pressure and to control or stop the encroachment of edgewater from the north and south. Water encroachment from the south was probably arrested by 1948, but encroachment on the north flank was still a serious problem; therefore, injection was continued. In Dec., 1951, crestal

pressures had been increased to the point that calculations based upon the then existing pressure gradients indicated the reservoir fluids were moving downstructure to the south, into water sands at the approximate rate of 5,500 B/D. Since continued injection of gas would only serve to aggravate the movement of reservoir fluids downdip to the south into the aquifer and also increase the size and fingering of the gas cap without halting the encroaching water from the north, gas injection operations were terminated in June, 1952.

During the following year continued observation of trends in pressure and production were made in this area to follow the equalization of reservoir pressure. However, in June, 1953, even though pressures were decreasing, the measured downdip driving force towards the south remained at the same high level. In order to reduce these crestal pressures a program was formulated which required producing crestal gas wells at high rates in an attempt to minimize migration losses without delay. This program incorporated the testing of the last line of downstructure wells in Sections 4G, 5G, and 6G in order to detect water movement at the earliest possible moment and also provide for the limited testing of wells located just within and outside the line of 1,000 GOR. The purpose of the latter test was to make reasonably certain that the reduction of upstructure pressure was not of such magnitude as to cause oil movement into a primary gas cap which would certainly result in loss of ultimate recovery.

In Jan., 1954, pressure data indicated that most of the south flank was approaching a balanced condition and the program was modified by shutting in all continuously producing wells in the area of high GOR. It is of interest to note that although 12 billion cu ft of gas were injected as of June, 1952, over and above the volumetric withdrawals during this same period, that it only required the removal of about 15 per cent of the net injection to return the reservoir to near its 1947 pressure distribution. It appeared that sufficient data had been accumulated to support the conclusion of large fluid losses out of the zone of injection, probably through an incompetent faulting system and wells completed in more than one zone, into the lower pressure sands of the SS-1 and/or other areas.

Subsequent pressure data indicated by May, 1954, that the adverse datum pressure gradients had in general been corrected and all upstructure test wells were shut in.

As the intercommunication between the SS-2 and M and the SS-1 sand had been proved, it was recognized that the pressure in the zone of injection would probably continue to decrease and that the area would not remain in balance as desired. Based upon an estimated rate of loss of fluids from the SS-2 and M, pressure maintenance by small scale gas injection was commenced in July, 1954. The purpose of injection was to attempt to maintain the SS-2 and M south flank sand at approximately its then present pressure and in a balanced condition. Sufficient information has not been accumulated at this time to measure the degree of success of this program.

Other Productive Zones

There are two other productive zones at Elk Hills. The Stevens Zone of Upper Miocene age is made up of both sand and fractured shale reservoirs. With a total of 224 producible wells development drilling is essentially complete in this zone. The Carneros Zone of Lower Miocene age is a recently discovered zone. Limited drilling to date has developed only condensate in the two productive sands in this zone.

Conclusions

It is believed that the development and readiness programs outlined in this paper have resulted in the development and maintenance of an oil field with large reserves that will be able to contribute a substantial addition to west coast oil production should it be called on to do so in any future emergency. Its current productive capacity is well in excess of 100,000 B/D over a sustained production period. The current estimate of recoverable oil in the Shallow Oil Zone is 330 million bbl. While an official estimate of the Stevens Zone Reserves is currently in progress and is not complete, other estimates indicate that the recoverable oil is about 400 million bbl. At this time no estimate has been made of the amount of recoverable oil in the Carneros Zone.

Since the total recoverable reserves are about 730 million bbl, it appears that the potential production from Elk Hills will remain a substantial percentage of California production for a long period of time.

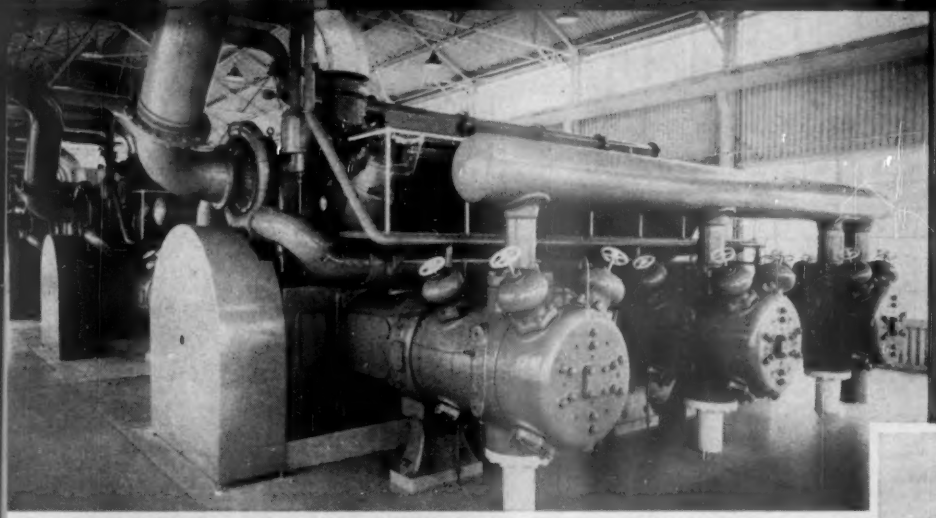
Acknowledgment

The writers express their appreciation for the contributions of the Operating and Engineering Committees. Particular appreciaiton is expressed to Rear Admiral H. P. Stolz, USNR, whose suggestion prompted this report, and to V. O. Wankowski for his assistance and criticism of this paper.

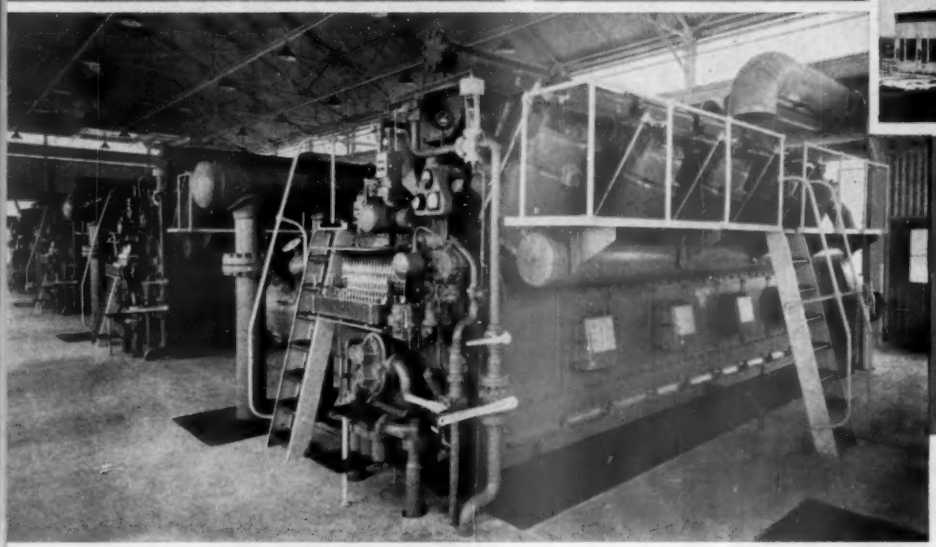
Acknowledgment is made to the Unit Operation Staff for their assistance in assembling much of the data. Appreciation is also extended to the Department of the Navy and the Standard Oil Co. of California for permission to publish this paper.

Reference

1. Eastman, M. C., and Ruhlman, F. L.: "Experimental Production Projects and Exploratory Drilling at Elk Hills," *Trans.* AIME (1948) **179**, 329. ★★★



These installation photos show the new Cooper-Bessemer GMVA compressors which are identical in both the Keyes, Oklahoma and Springfield, Colorado transmission stations of the Colorado Interstate Gas Company. Below are exterior views of the compact Keyes (left) and Springfield (right) stations.



Another Example of Efficient Power at Lower Cost

The latest for Colorado Interstate Gas . . .

COOPER-BESSEMER GMVA's

for new highs in compressor performance

● Two important transmission stations of the Colorado Interstate Gas Company have installed new Cooper-Bessemer GMVA compressors with centrifugal blowers.

Both the Springfield, Colorado and Keyes, Oklahoma stations are equipped with four of these big, modern 10-cylinder GMVA's rated 1350 hp at 300 rpm. The GMVA compressor is an *even better, smoother operating* unit than the well-known GMV it replaces.

With the GMVA, there's a 10% reduction in fuel consumption, good air ratio to all loads, higher horsepower ratings with no space increase, operation on a variety of fuels, ample working space around power cylinders . . . and many other advantages that add up to increased compressor operating efficiency and reduced maintenance demands in the 540-1350 horsepower range.

For further information on the dependable and economical GMVA, drop in, or write to any of the conveniently located offices listed below. You'll be especially interested in Cooper-Bessemer's new, complete GMVA Catalog No. 75. Write for your copy today.

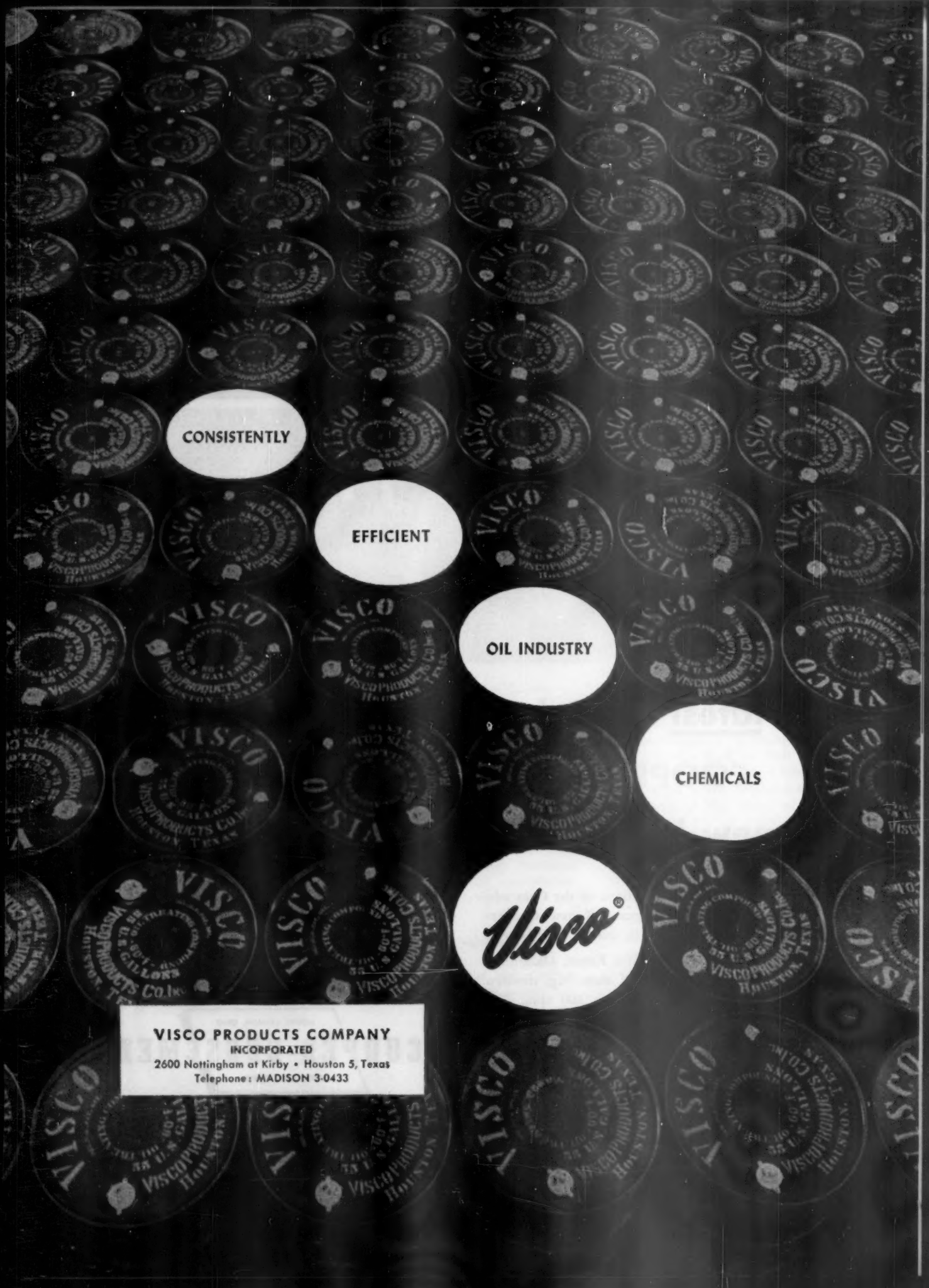
MOUNT VERNON, OHIO

COOPER-BESSEMER

GROVE CITY, PENNA.

New York City • Seattle, Wash. • Bradford, Pa. • Chicago, Ill. Houston, Dallas, Greggton, Pampa and Odessa, Texas Washington, D. C. • Shreveport, La. • San Francisco, Los Angeles, Calif. • St. Louis, Mo. • Gloucester, Mass. • New Orleans, La. • Tulsa, Okla. • Cooper-Bessemer of Canada Ltd., Edmonton, Alberta—Halifax, Nova Scotia.

DIESELS • GAS ENGINES • GAS-DIESELS • ENGINE-DRIVEN AND MOTOR-DRIVEN COMPRESSORS


CONSISTENTLY
EFFICIENT
OIL INDUSTRY
CHEMICALS
Visco®
VISCO PRODUCTS COMPANY
INCORPORATED
2600 Nottingham at Kirby • Houston 5, Texas
Telephone: MADISON 3-0433

save 15 to 30 minutes on every round trip!

PB SAFE-LOK DRILL PIPE AND CASING PROTECTORS

IT'S AS SIMPLE AS THIS . . .

Place the Safe-Lok around the pipe and engage the lock.

With the special Safe-Lok wrench, make one-half turn to the right.

Write for Safe-Lok Bulletin No. BJO-737.

Includes detailed clearance chart to be used in selecting protectors. Also gives complete size and price information.

Your own crew can install or remove PB Safe-Lok Protectors in seconds—using just a simple wrench. You eliminate the time and trouble of laying down and picking up rubbered pipe on round trips. Simply remove the Safe-Lok Protectors from the top of your string as you come out of the hole . . . use this unrubbered pipe for bottom service when you go back in . . . and reinstall the Safe-Loks on the new top-hole pipe.

Field records prove that 15 to 30 minutes can be saved per round trip with this Safe-Lok method. Based on an average big rig drilling cost of a dollar per minute, these protectors soon pay for themselves in rig time saved . . . and continue to save you dollars on every trip.

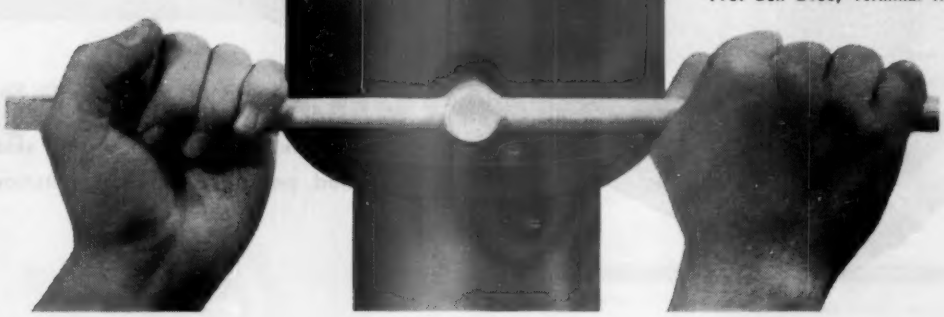
Safe-Lok Protectors are available in a range of sizes and lengths for drill pipe and kelly subs from 3½" to 5½" O.D. Ask any BJ-PB field sales engineer or write for Bulletin No. BJO-737.

BJ SINCE 1872

Byron Jackson

DIVISION OF BORG-WARNER CORPORATION

P.O. Box 2493, Terminal Annex, Los Angeles 54, Calif.



EXPORT ADDRESS:
580 Fifth Avenue,
Suite 510
New York 36, New York
PLaza 7-0400

NOW...a new and more powerful

HORSEPOWER INCREASED 25% IN HMAB

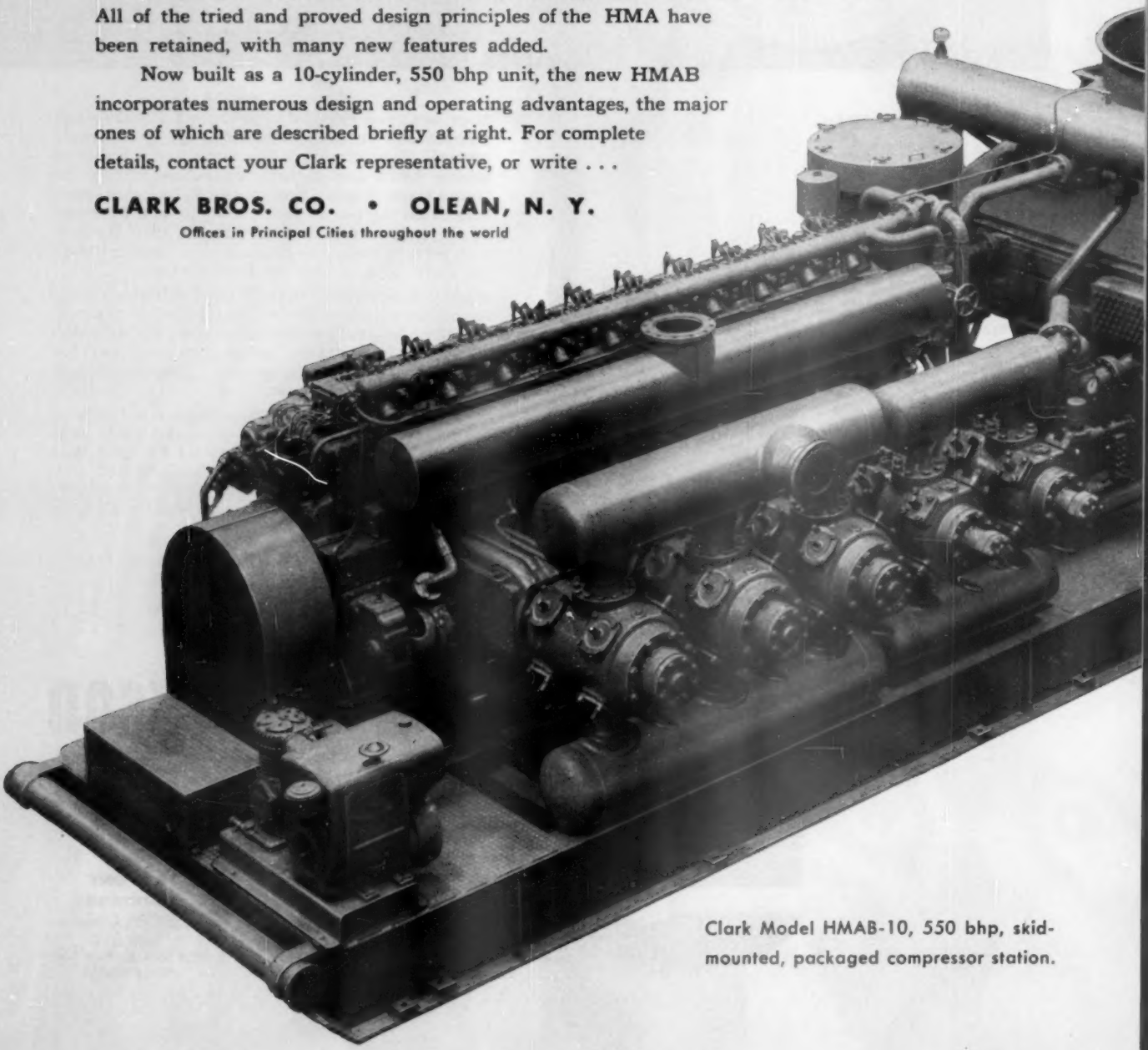
Out of the experience gained in more than 10 years of building hundreds of "Midget Angles" for field service, Clark has developed the new and more powerful HMAB.

It delivers 25% more horsepower than the famed Clark HMA line (which will continue to be built). It meets the need for a more powerful, skid-mounted, factory-packaged unit, without an appreciable increase in dimensions. All of the tried and proved design principles of the HMA have been retained, with many new features added.

Now built as a 10-cylinder, 550 bhp unit, the new HMAB incorporates numerous design and operating advantages, the major ones of which are described briefly at right. For complete details, contact your Clark representative, or write . . .

CLARK BROS. CO. • OLEAN, N. Y.

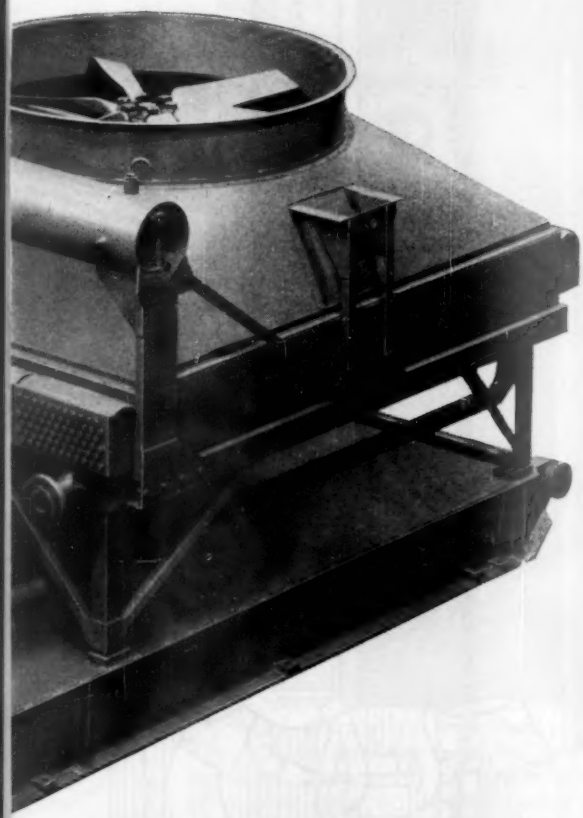
Offices in Principal Cities throughout the world



Clark Model HMAB-10, 550 bhp, skid-mounted, packaged compressor station.

CLARK "MIDGET ANGLE"

COMPRESSOR



CLARK®

ONE OF THE DRESSER INDUSTRIES

COMPRESSORS

COMPRESSOR

HEAVIER IN ALL RESPECTS
Not just a re-rated HMA.

GREATER ENGINE DISPLACEMENT
8 ⅝" bore by 8 ⅞" stroke.

NEW, HEAVIER, UPPER AND LOWER CRANKCASES

NEW LINER, HEAD AND PISTON DESIGNS

NEW, HEAVIER CONNECTING RODS

NEW, HEAVIER CROSSHEAD AND CROSSHEAD PINS

NEW, FULLY INSULATED EXHAUST MANIFOLD
Saves 25% on engine cooling.

NEW, CHAIN-DRIVEN, ENGINE-MOUNTED WATER PUMP

NEW, EXTERNAL LUBE OIL PUMP

SAME, VIBRATION-FREE, BALANCED/OPPOSED DESIGN

RADIATOR

NEW, INDUCED, VERTICAL AIR FLOW
For improved cooling efficiency.

SUBSTANTIALLY GREATER COOLING CAPACITY

LOW, CLOSE-TO-SKID DESIGN
Eliminates vibration.

HYDRAULIC MOTOR, FAN DRIVE
Eliminates belts and counter shafts. Flywheel driven pump supplies fluid power.

STRAIGHT, FINNED TUBES
Removable header plugs permit visual inspection.

SIMPLE PIPING ARRANGEMENT
Easy access to scrubbers.

COOLING SURFACES SPREAD OUT
Permit closer approach to ambient temperature.

HIGHWAY WIDTH
Need not be removed from skid for shipping.

SKID

NEW, BOX TYPE CONSTRUCTION
Extra deep I-Beam and straight-through cross members highly resistant to bending and twisting.

SIMPLE TO INSTALL
Only two members to grout in.

HIGHWAY WIDTH
All piping confined to skid width.

YOUR BEST
CONNECTION IS

HYDRIL

Greater strength with smaller size... inside and outside pressure seals... faster make-up and break-out time... these are the payoff characteristics of all HYDRIL JOINTS... drill pipe, casing, or tubing.

Consult your HYDRIL field man for more detailed information, or see pages 2504 to 2536 of Composite Catalog.

HYDRIL COMPANY

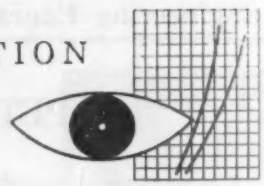
714 W. OLYMPIC BLVD., LOS ANGELES 15, CALIF.

FACTORIES AT

LOS ANGELES; HOUSTON, TEXAS; YOUNGSTOWN, OHIO; ROCHESTER, PA.

HYDRIL SALES OFFICES

California: Bakersfield, Los Angeles, Ventura;
Louisiana: Harvey, New Iberia, New Orleans;
Oklahoma: Tulsa; Pennsylvania: Rochester;
Texas: Corpus Christi, Dallas, Houston, Midland, Odessa; Wyoming: Casper;
Canada: Calgary, Edmonton.



JOSEPH B. UMPLEBY
MEMBER AIME

GEOLOGIST AND ENGINEER
DALLAS, TEX.

PETROLEUM ENGINEER STUDIES SHOULD EMPHASIZE COSTS

Petroleum engineering has probably experienced the most rapid and widespread growth of any of the engineering professions. In the mining industry for many generations finding, extraction and beneficiation had been directed by men specially trained in each particular field. The petroleum industry, in contrast, used geologists and refining technicians in the early twenties, but that great middle ground of production was wholly unoccupied by technically trained men.

Prior to 1925 when AIME entered the field, there was no open forum for the discussion of production problems. Late in 1927 the American Petroleum Institute first recognized petroleum engineering among its many branches. The first attempt at a handbook was *Petroleum Production Methods*, by John R. Suman, in 1921. Three years later came *Petroleum Production Engineering*, by L. C. Uren—the first textbook. As late as 1926 only six schools offered special courses in the subject; two years earlier there had been only three. The early engineers in production were recruited from mechanical, civil, and chemical schools. Many geologists with some engineering background entered the field.

Early Statement on Cost Emphasis

Upon this foundation the profession has grown and now reaches into every area in the world where oil is produced or where drilling is in progress. Its members are numbered in the thousands and scores of schools offer organized courses. In discussing the rapid growth and recognition of the profession as retiring Chairman of Production Engineering for 1927, I said in part:[1]

> "I believe . . . that recognition is due principally to economic pressures within the industry which have directed attention more and more sharply on costs and efficiency.[2] After all, the justification for the growth and continued development of the profession is to recover more oil from a given unit of sand at less cost per barrel. In this new profession, it seems to me, the greatest progress will result from focusing thought and effort on this single objective, and if I might offer a suggestion to the committee for 1928 it would be to get more cost data into the record than my committee has done."

I still believe that the petroleum engineer should have costs deeply imbedded in his mental processes. A definition, perhaps as good as any other, of the petroleum engineer would be: "A man well trained in the fundamentals of engineering as applied to oil, who has absorbed much from the geologist on the one hand, and the economist on the other." The latter, I believe, has not received as much emphasis in college training as it deserves.

[1]AIME *Pet. Dev. & Tech.*, 1927, pp. 11-18.
[2]Following World War I the price of crude fell sharply and many feared the industry would be faced with one dollar oil.

Lowest Possible Cost Per Barrel

In oil recovery problems the dollar and the barrel are inseparable. The central objective of the petroleum engineer is to recover the most possible oil from the reservoir at the lowest possible cost per barrel. The equation should balance. From the first day in the first class in operating techniques, on through later courses, the cost of doing things should be kept constantly before the student with the idea of making it a part of his mental reactions. Keeping at least one foot on the ground from a practical standpoint need not lessen his urge for progress through investigation. He only need ask himself, if it works will it pay a profit, and how is that profit related to the cost of finding out?

Consideration of the above problem suggests a special course in petroleum economics as the solution. But this offers difficulties and I believe it is not the most effective approach. The difficulties involve: (1) finding a man competent to teach it and give vitality; and (2) finding room for a special course in a crowded curriculum.

Instead of a special course in economics I believe better results would follow if instructors in many different specialized courses worked cost data into their presentation. If the skillful instructor is as cost-conscious as he should be, he can find innumerable ways of weaving economic principals into his discussions without appreciably reducing the coverage of his course. In fact he will find that it stimulates interest. I tried this in my own courses at the University of Oklahoma and was gratified at the results. Several former students, now around 25 years out of school, have mentioned it and gone out of their way in expressing appreciation.

Good Management Material

The basic reason, other things being equal, why the engineer is good management material is his training in quantitative thinking. Fundamentally engineering is a precision subject like mathematics, physics and chemistry. In contrast geology is largely a qualitative subject with emphasis on observation and deduction. Of course many individuals cross the line by reason of natural bent or exposure, but that fact should not lessen recognition of the basic difference in mental training. To the petroleum engineer's training in precise thinking add his position in the great middle section of the industry entailing a wide knowledge of the cost of doing things, and we have a natural for management, providing only that the generally recognized personal qualifications are met. These general qualificiaions—personality, aggressiveness, leadership, etc.—probably characterize about the same percentage of personnel in all professions.

The opportunities for the petroleum engineer are limitless. Chances for advancement are exceptional. He posses the basic potential. What he makes of it as an individual is in substantial part his to determine. ★★★

Engineering Education Report 3 on

PETROLEUM ENGINEERING ENROLLMENT

The problem of availability of engineering graduates is one of considerable concern to both industry and universities, and it should be of even greater concern to society in general. Most universities had to turn down recruiters early this spring because there were no more available prospective graduates. In many cases the recruiters seemed to feel that the universities were to blame for such a situation, which, of course, is far from the facts in the case.

The statistics of university enrollments balanced against industry and governmental requirements indicate that conditions will become progressively worse for the next several years. For 1955 there will be 460 graduates in petroleum engineering with BS degrees from accredited schools, and possibly 550 all told. Even though many engineers with other training will be employed, this is very few for an industry with over $10 billion of investments.

Deficiency of Good High School Grads

Most educational institutions at the university level would be happy to have more well qualified students, but the supply appears to be limited at the source. This goes back to the secondary schools throughout the nation. In spite of our mechanical age and all of its wonders, there is a growing deficiency of good high school graduates who are taking engineering courses. Most engineering colleges have found that current high school graduates are not properly trained to start work on an engineering degree. This problem appears to be widespread and not due to local conditions.

There are probably several rather deep seated reasons for the above conditions. Some of the possible reasons may be: an attempt to by-pass the more difficult courses, poor counselling as to courses, inadequate teaching staff, and lack of interest of the parents, industry and society. It goes without saying that mathematics and the basic sciences are generally more difficult than many courses offered in the average high school curriculum. It therefore is necessary that the student either have a strong personal urge or that the importance of the subject matter be stressed by his elders. The furnishing of sufficient incentives is thus a problem that cannot be overlooked.

High Mortality Rate

Poor counselling and an inadequate teaching staff are more or less the same problem. It is quite probable that if the staff were adequate, the qualified students would be urged to take the necessary courses. It is reported, however, that well-trained mathematics and science teachers are in great shortage at the high school level. Recent surveys have shown that "of the small group of high school students graduating in the upper quarter of their classes, about 47 per cent fail to continue formal education, and another 13 per cent drop out before completing college. . . . and only 2 per cent . . . continue their education through the PhD level." Furthermore in the face of mounting high-school enrollment, "Between 1950 and 1954, the number of college graduates meeting . . . requirements to teach . . . mathematics and science in high schools dropped 51 and 56 per cent respectively, . . . and that only 40 per cent of these 1953 . . . graduates were teaching in November of that year."

It therefore is obvious that counsellors cannot recommend students to take courses if no good teachers, or none at all, are available.

As a result of the above situation many colleges find it necessary to admit students with deficiencies in science. Such a situation immediately puts the student in an inferior position which may not have been his fault. It also stretches out the normal college engineering course to five years, which is wasteful of time and money—especially in view of the selective service problem which is superimposed on the other. As a result of inadequate preparation, many students who would normally graduate as good engineers become discouraged and are permanently lost to the profession, to industry, and to the nation. This is undoubtedly one of the contributing factors to the high mortality rate of student engineers, especially in the first two years.

The Importance of Engineers

This raises the question of a solution. Naturally there is no easy or simple answer. It must be handled by careful deliberation by everyone concerned. It appears to most college educators that they should not intrude into the problems of the high schools, after they have pointed out the situation. Most of us feel that industry and the professions should assume the responsibility of knowing whether or not high school students are being adequately trained, and if students in their early adolescence are advised as to the more worthwhile things in life and the necessity of working and preparing one's self for a most productive future. This is a place where the AIME members as individuals and as an organization should join with all other engineering groups to promote the prestige and knowledge of the merits and accomplishments of engineers, as well as to instill in young men the desire to be the best engineers possible.

Most important of all, is that society should recognize the value and importance of engineers. I am sure that engineers, as a group, have contributed more to our material progress as a nation than any other group, and I am also convinced that society recognizes this fact. It is therefore our duty to keep society advised of the current status of engineers, and the necessity for much greater encouragement for our youth to study and practice engineering. This is the duty of the individual and the engineering societies. It is even more important that industry and the government recognize the situation and do something concrete about it, for in the final analysis they have the greatest stakes in the problem.

A. W. WALKER, *Chairman*
Education Committee

PERSONALS *of Petroleum Branch Members*

J. W. W. WHITNEY, JR. is now chief production engineer with Helmerich & Payne, Inc. He was graduated from the University of Tulsa with a BS in petroleum engineering in 1949 and immediately went to work for Magnolia Petroleum Co. as a petroleum engineer trainee. Later he served as district petroleum engineer for Magnolia in Wewoka, Okla., and Electra, Tex.

☆

ERNEST G. HOTZE, assistant manager of Clark Bros.'s Houston district territory, has been promoted to district manager. Hotze began his career in the oil and gas industry in 1935 with Cities Service Oil Co. in Oklahoma City. He joined Clark as a sales engineer in 1942.

☆

MALCOLM D. ABEL has been promoted to West Texas Div. manager of the B B M Drilling Co. In his new capacity he will supervise rotary drilling tools and production development. Abel received his degree in petroleum engineering from the University of Texas in 1947 and while in school was president of the local chapter of AIME.

ED T. HEWITT is now in charge of the New York main office of ESCO International, a new export division established by Electric Steel Foundry Co., Portland, Ore. Hewitt was with Electric Steel Foundry Co. prior to this appointment.

☆

JOHN G. RICHARDS, formerly a reserves and valuation engineer with The Texas Co., has joined the staff at The Fort Worth National Bank as a petroleum engineer in the Oil Loan Div. He holds a BS degree in mechanical engineering from the University of Oklahoma.

☆

R. R. SHAFFER, petroleum engineer for Ohio Oil Co., has been appointed treasurer of the San Joaquin Valley Section of AIME. He replaces W. B. EMERY II who has been transferred from the Bakersfield area to the Los Angeles area.

☆

CLYDE M. KEITHLY has opened a petroleum engineering consulting office in Austin, specializing in Railroad Commission hearings, oil and gas property appraisals and unitization. His partnership in the firm of Pinkston, Miller and Keithly was terminated on Sept. 30, 1955.

☆

PETE DE FRANK has been appointed assistant manager of the Research Section of Welex Jet Services, Inc. Before joining Welex he was associated with Humble for seven years and was in charge of the perforating testing laboratory for that company. He holds a BS degree in chemical engineering from Texas A&M.

HAL J. JONES, director of Geophysical Research in the TI Research Div., in Dallas, has accepted a new appointment as chief engineer of Houston Technical Laboratories, petroleum instrumentation subsidiary of Texas Instruments, Inc. Before joining Texas Instruments, he was research engineer and party chief of the geophysical research group at Stanolind Oil & Gas Corp. and prior to that was associated with Engineering Research Associates and the Shell Oil Co.

☆

WILLIAM E. BROWN (left) and BERNARD JACKNIN, research associates with the Western Co., will open the Midland firm's new research facility at Dallas. Brown holds a doctorate in physical chemistry from Rutgers University, and came to Western after five years with Gulf Research and Development Co. where he served as senior scientist in the geological and geochemistry division. Jacknin is a registered professional engineer with a PhD in chemical engineering from Virginia Polytechnic Institute. Previously he was assistant to the director of engineering and development at Congoleum-Nairn, Inc. The new facility will extend the research and development work carried on by the company at its headquarters.

☆

L. M. STEVENS is now with Aztec Oil & Gas Co., Dallas.

BRANCH CHAIRMAN TELLS of ACCOMPLISHMENTS in 1955

ROBERT B. GILMORE
MEMBER AIME

CHAIRMAN
PETROLEUM BRANCH, AIME

Former Chairman John McMillan's report last year indicated a year so successful that I thought it would be impossible for us to show a better record. What has happened? Thanks to the efforts of each of you, particularly the officers of the local sections, our many committee members, members of the Executive Committee, Institute staff, and most especially to our own staff and to Joe Alford, we did it.

I like to think this is a unique organization where everybody is willing to take on any job that they are asked to do and do it well. So far this year we have not had an appointment refused by anyone, and all are doing a fine job. But it's not the organization that is the cause of such excellent cooperation, it is the fine people who are its members. We get out of our professional society what we put in it, just the same as any other endeavor. Let us look now at what we have gotten out of the Petroleum Branch and the AIME recently.

$32 Spent Per Member

Usually, the first thought that stirs our intellect is money. We as members do not get any directly, but look what the Branch spends for us — excluding for the time being the Special Projects Fund.

With eight months gone it looks like total expenses will be $240,000, or some $32.00 per member. The majority of this, 56 per cent, goes for publications such as the JOURNAL OF PETROLEUM TECHNOLOGY, *Transactions* volumes, *Statistics* and the like. This is accepted as normal, since through these publications we perform our primary function as a professional society — our mental meeting ground.

Next in importance, of course, is the 23 per cent we will spend directly on the members — money paid to local sections, operation of our technical divisions, special membership activity, the results of which are so evident today, plus some Institute activities — our physical meeting ground.

The remaining 21 per cent covers our necessities, the business end of our operations, including pensions for our staff employees, insurance, depreciation, and all the other costs normal to any operation of such magnitude — maintenance of our healthy condition.

In the Black

That is a sizeable budget, but we still manage to take in more than we spend. The Executive Committee would rather operate in the black than appoint committees. This year our profit margin looks like $10,000-plus*, compared with our actual margin of $6,000 last year. Where do we get it all? Dues, of course, are the most direct extraction — representing 43 per cent of total income. We get another 10 per cent from new members, thanks to the membership campaign you have been conducting so successfully. Practically all of remaining income is from publications — not from selling them to you so much as selling them to advertisers of the products we buy and use.

Thirty-four per cent of our total income is from sales of advertising space in the JOURNAL OF PETROLEUM TECHNOLOGY, and here is where every one of you can take part in our continued success. The next time you buy a drilling rig, a bit, a packer, some acid or cement, tell them you saw their ad in the JOURNAL OF PETROLEUM TECHNOLOGY. Those of you who may be in a position to influence your company's advertising could put in a plug for PETROLEUM TECHNOLOGY, the magazine for the analytical men in the petroleum industry. Let's sell ourselves as well as the public. For example, if you have to use Atlas tires and batteries, you might as well read ads in your own magazine on how good they are and feel better about it.

Most of the remaining 13 per cent of our income for this year, which should hit $250,000, is from sales of *Transactions* and *Statistics* volumes. The rest is from PETROLEUM TECHNOLOGY and miscellaneous sales.

More Services, Less Dues

We might turn the page and take a look into the future if it can be done without charting a course for the new administration. Assuming no major change in the basic economy nor in the operation of the Branch, it

Robert B. Gilmore is a vice-president of DeGolyer and MacNaughton, Dallas.

*Editor's Note: A decision has been made to spend an additional $2,000 for publication of more Technical Papers in the November and December issues of JOURNAL OF PETROLEUM TECHNOLOGY. This will reduce the anticipated profit to $8,000.

looks like our income in 1956 ought to increase 15 per cent over this year. Expenses are projected at an increase of only 4 per cent, which indicates a more substantial profit which could be as much as $40,000. Two years from now on the same projection it looks like we could show a profit of $60,000 plus a little — both of these projections are based on our economy remaining somewhere near the present level.

I do not think we want to build up a big surplus. We cannot pay dividends just for belonging to the Petroleum Branch, but we can reduce dues. Each Executive Committee has had this in mind since dues reached their present level. We also can begin to see the possibility that our *Transactions* and *Statistics* volumes will return to their status of free of additional cost to members.

These are rosy predictions. Can we back them up? Let's look at membership activities. You will remember our membership promotion last year. We have continued this year to invest our time and money in this effort and the results continue to be favorable. Through September we have received 701 new applications*, or 15 per cent more than last year. The Gulf Coast Section is due a round of applause for apparently walking away with the contest with 174 new applications so far this year. The rest of the sections will have to turn in about five times as many as they already have in the next three months to catch them. Oklahoma City, East Texas, and Panhandle sections also are doing good in their groups, but you other sections can catch them if you try.

Reprinting of Transactions

Our last comparable figures show the Petroleum Branch with 7,900 members out of 25,000 in the Institute, or almost one-third. We have been making a special effort this year for Student Associates, and 473 are included in the 7,900 total. We have a fine crop of Junior Members too with 2,842. With a little effort on the part of all our 26 sections, we ought to be able to show further substantial increases in Associate Members (of which we have 766) as well as in all the other grades.

Now let's consider our financial situation to include the Special Projects Fund. By the end of this year this Petroleum Branch fund is expected to exceed $40,000, or an increase of some 20 per cent over last year. Plans now under consideration contemplate using part or all of this account in publications, which should return profit commensurate with the amount invested. As indicated by questionnaires you have received, the demand for back copies of the *Transactions* volumes is great enough that this probably will soon be undertaken. We also are making progress with our plans to print next year a book concerning economics and world supply and demand, the basic work for which has been and is being done by Arabian-American Oil Co. It is a fine study containing many charts of valuable facts and data and represents the expenditure of considerable time and money by this company. We are fortunate in having the opportunity to sponsor its publication.

*Editor's Note: Through Oct. 31, 1955, 918 applications have been received, or 30.2 per cent more than at this time last year.

1956 Annual Meeting

While talking of the future I would like to point out that the AIME Annual Meeting in New York next February is going to be different. We have saddled our New York Petroleum Section with all of the responsibility for that meeting. Their program is not complete yet, but in general the papers delivered will be broader in scope than those given here and will cover such subjects as economics, financing, and the position of the petroleum engineer in the management side of the industry. The New York Section also has agreed to handle such Petroleum Branch social activities as can be scheduled, and as you know their resources are almost unlimited. If this gets to be too big a chore, maybe we can trade off with our Venezuela Section and hold a meeting in Caracas once in a while.

Our Education Committee, under the chairmanship of A. W. Walker, Tulsa University, has been working diligently. It is as much our responsibility as that of any other group or society to encourage more students to take engineering. We should consult and assist our educators so that the training they give will be of maximum benefit to us, to our fellow employees, to the industry, and to the nation.

New Petroleum Engineering Award

It now is my pleasure to announce that as soon as the mechanics can be arranged, the Petroleum Branch will be the donor of a new award for outstanding work in petroleum engineering. With broad requirements, this award will take its place among the foremost awards in the industry and will be valued highly. The initial contribution for the award as well as the idea for its founding has been made by Lewis W. MacNaughton, with whom I have been closely associated for several years. It will be named in honor of John F. Carll, whose ideas and writings first expressed principles of petroleum engineering which we now consider commonplace. His example of a bottle of soda, or a barrel of beer, has become a classic. This award not only will be a permanent plaque or medal, but will be accompanied by a book, suitably inscribed, historically viewing Carll's theories and accomplishments together with other early manifestations of our profession. It is our hope and plan that our eminent historian and honored member, E. DeGolyer, will assist in the preparation of this treatise.

All in all, our accomplishments this year may appear to be routine, but the enthusiasm of you members for this professional society marks even more clearly the distinction between us amateurs who occasionally are projected into some executive position and you pros who really run it. ★★★

Over
50
Locations in the United States and Canada

McCullough® REPORTS TO THE OIL INDUSTRY

Service
Anywhere Anytime

New Services • • • New Tools • • • New Methods • • • Outstanding Results

Locates Pay Sand Missed by Electric Log

In a shallow well in Oklahoma the McCullough Radiation Well Log picked up 23′ of pay that had been missed by an electric log.

The electric log had picked a hard limestone as the pay zone 5½" O.D., 14 lb. casing was set to bottom. Limestone formation was perforated and found dry. Then McCullough was called to run a Gamma Ray Log. At approximately 1100′, and just below the hard limestone, the McCullough Log picked up 23′ of shaley pay sand. This entire productive zone had been missed by the electric log.

The accurate and reliable information supplied by the McCullough Radiation Well Log (Gamma Ray and Neutron Curves) provides a sound basis for perforating for completion . . . always Log AND Perforate by McCullough.

Efficiency of McCullough Services Saves Operator Valuable Rig Time

Only 7½ hours were required to log, perforate and set a packer in this Texas well.

5½" O.D., 17 lb. casing was cemented at 7716′. Well was logged by McCullough from 7716′ to 5000′, obtaining gamma ray and neutron curves and recording a simultaneous collar log. Twenty McCullough Standard Casing Glass Jets, four per foot, were shot in the interval from 7482′ to 7487′. This was followed by setting a production packer at 6410′

In this series of operations there was no delay of any kind – a tribute to the efficiency of McCullough tools and instruments and to the skill of McCullough service crews

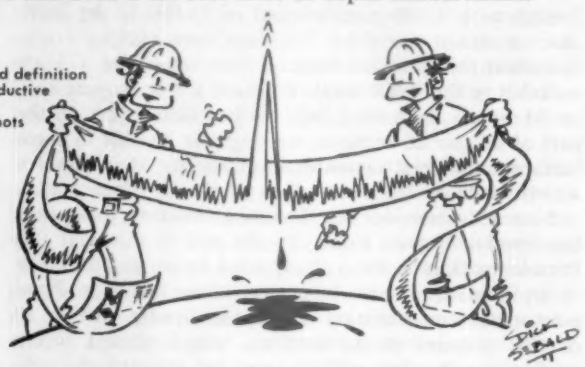
$2,433.21 SAVED

Accuracy of McCullough Radiation Well Log Prevents Wasting 390 Perforating Shots in Non-productive Shale Zones... Helps Increase Production 178 B/D

The decision to run a McCullough Radiation Well Log was worth $2,433.21 to this California operator 390 shots would have been wasted in dry shales except for the discovery of a ten-foot error in electric log measurements.

Well had been bottomed at 11,237′ and the electric log was run in open hole. A 5½" O.D., 23 lb. slotted liner was set through the productive interval. Well was put on production and slowly settled down to 22 barrels per day.

Operator decided to perforate liner to attempt to increase production. It was known that there were eight zones separated by shale beds to be perforated. A McCullough Radiation Well Log was run to exactly locate these zones and to check previous measurements. When correlated with the old electric log it was found that there had been a ten-foot error in depth measurement.



Exact measurement and definition of any potentially productive interval, thick or thin, assures "putting the shots where they count" for greater production — more oil!

The eight zones were perforated with a total of 1332 shots, four holes per foot, from the detailed data provided by the McCullough Log. 660 of these were ½" improved Ogival Bullets fired by 3½" O.D., McCullough M-3 guns, 2 holes per foot. The remaining 672 shots were fired by McCullough Standard Casing Glass Jets with Steel Strip Carriers, 2 holes per foot.

Production increased from 22 to 200 barrels of oil per day.

This job particularly emphasizes the extreme value of the accuracy and efficiency of the McCullough Radiation Well Log to the operator. Engineers of this company estimated that, had the well been shot by the old electric log measurements, 390 of the 1332 shots would have been placed in the non-productive shale beds separating the pay zones. At prevailing prices this would have meant a loss of $2,433.21 because of wasted shots. In addition the resulting production would have been considerably lower because of improper coverage of the eight zones.

It always pays to run a McCullough Radiation Well Log before perforating.

McCullough® *TOOL COMPANY*

Cable Address: MACTOOL

LOS ANGELES
HOUSTON
EDMONTON

We're closer than your telephone....

At Hughes we like to feel that our rock bit service puts us closer than your telephone. For Hughes service requires that each field representative know *in advance* — through personal contact — the bit requirements of the rigs drilling in his area ... and have the right bits on these rigs ... *ahead of time!* Through our experienced service organizations we serve every active drilling area in the United States and Canada.

We cover the "wildcats", too!

Ours is not a spot service. The more than four hundred members of Hughes Tool Company's service and sales organization cover every active drilling area in the United States and Canada.

You can be sure that the Hughes field serviceman who calls at your rig — regardless of where it is located — will have the right bits there . . . *ahead of time!*

Along with your Hughes bits you get the industry's greatest accumulation of drilling information . . . gathered from hundreds of thousands of wells and from every type of formation.

For Membership Applications

NEW RECORD SET in OCTOBER

VIRGINIA B. DAGGETT | *ASSISTANT SECRETARY PETROLEUM BRANCH, AIME*

October brought in 186 new applications for membership, breaking previous records for any single month. The total of 918 applications in the first 10 months is up 30.2 per cent over the same period last year, when 705 applications had been counted.

Contest standings shifted somewhat in all groups, with the Gulf Coast and Panhandle Sections retaining their leads in groups D and A. Denver Petroleum and Kansas nosed out East Texas to tie for first place in Group B, and Venezuela Petroleum jumped from third to first place in Group C. Standings of all sections are shown in the table at the right.

PETROLEUM BRANCH MEMBERSHIP CONTEST

Ten-Months Report

Covering Applications Received Jan. 1-Oct. 31, 1955

Section	Jan. 1 Membership	Applications Received	Per Cent Increase
Group A			
1. Panhandle	60	19	31.7
2. Hobbs	88	26	29.5
3. Mississippi	59	12	20.3
4. Billings			
Petroleum	61	12	19.7
5. Hugoton	27	5	18.5
6. North Texas	84	13	15.5
7. South Plains	51	1	2.0
Group B			
1. Denver			
Petroleum	141	27	19.1
Kansas	141	27	19.1
2. East Texas	141	25	17.7
3. Lou-Ark	148	19	12.8
4. Wyoming	152	13	8.6
5. West Central			
Texas	135	10	7.4
6. Illinois Basin			
Petroleum	154	8	5.2
Group C			
1. Venezuela			
Petroleum	194	29	14.9
2. Delta	308	45	14.6
3. Oklahoma City	269	34	12.6
4. Fort Worth	181	21	11.6
5. Permian Basin	352	30	8.5
6. San Joaquin			
Valley	169	12	7.1
7. New York			
Petroleum	212	14	6.6
Group D			
1. Gulf Coast	929	223	24.0
2. Mid-Continent	553	68	12.3
3. Southwest Texas	461	54	11.7
4. Dallas	433	50	11.5
5. Southern California Petroleum	597	38	6.4
Total Applications from Sections		835	
Miscellaneous		42	
Foreign		41	
Total Applications Received Jan. 1-Oct. 31		918	

Proposed for Membership, Petroleum Branch, AIME

TOTAL AIME membership on Aug. 31, 1955, was 23,194; in addition 1,903 Student Associates were enrolled.

PETROLEUM BRANCH ADMISSIONS COMMITTEE

Virgil B. Harris, chairman; C. C. Harter; Charles Hudson; Raoul J. Bethancourt; Oscar K. McElheney; Jack Wahl.

Arkansas

El Dorado—Zimmerman, O. Frank, Jr. (R, C/S-J-M).
Hope—Evans, Richard Roy (R, C/S-S-J).
Magnolia—Dettmers, Kurt Alfred (J).

California

Bakersfield—Benton, Thomas Harrison (M); Black, Joseph L., Jr. (R, C/S-S-J).
Fullerton—Hamilton, Ramon K. (A).
Garden Grove—Patton, Dale Joseph (J).
Long Beach—Garrison, Erskine Pope (M); Glass, Norman Keith (J).
Los Angeles—Choate, Lee R. (A); Loeb, Joseph Harry (J); McKenna, Warren Preston (A); Payne, W. S., Jr. (M).
Pacific Palisades—Halliburton, David John (A).
Whittier—Bowden, Charles F. (M).

Colorado

Denver—Dolan, John Patrick (M); Garrison, Marion Ames (M); Henderson, Hubert Gerald (R, C/S-S-A); Higgins, Richard A. (M); Jersin, Arthur Joseph (R, C/S-S-M); Parker, H. Leslie (A).

Kansas

Great Bend—Lehman, John Joseph (M); Raymond, Louis Edward (J); Stover, Robert Louis (M); Swanson, Emery Weston (A).
Wichita—Griggs, Jack Sandifer (J); McLaughlin, Philip Lyle (M); Peel, Herbert Logan (J); Pursifull, Wilbur Dean (J).

Kentucky

Ashland—Sturm, Paul William (M).

Louisiana

Bossier City—Sawyer, Earl (A).
Ferriday—Arze, George Mario (R, C/S-S-J).
Harvey—Petty, Orwin Earl (M); Whittington, Hiram A. (J); Zambon, Edward Joseph (J).
Houma—Laenger, Ralph Ernest (J).
Lafayette—Biehl, Lester E. (R, C/S-S-M); Driskill, James David, Jr. (M); Featherston, Henry Edwin (M); Lohn, Cecil Eugene (M); Motter, Eugene Francis (J).
Lake Charles—Claus, Clyde Robert (M); Duke, David H. (R, M); Tindell, William Arthur, Jr. (R, C/S-S-J).
Metairie—Todd, William Arledge (M).
New Iberia—Rhoades, Frank Leslie, Jr. (M); Robbins, Philip Leonard (M).
New Orleans—Cook, Lodwrick Monroe (J); Folwell, Robert Charles (J); Gower, George Hardesty (A); Jenson, Philip Everett (J); Scarborough, George Benjamin (J); Schwab, Carl Frederick (M).
Olla—Carter, Marvin Ray (J).
Shreveport—Burton, Ralph Philip (M); Golding, Bert Henry (C/S-J-M); Redford, William Hamlet, Jr. (M); Stewart, Joseph Bernard (M); Zimmerman, Ramon William (J).
Triumph—Aunspaugh, Dale Harris (J).
Venice—Crews, Louis Sherwood (J).

Mississippi

Brookhaven—Denyer, Robert Gilmore (M).

Montana

Billings—Howell, Ernest (M); McClure, Joseph A., Jr. (M).

New Jersey

Montclair—Johnson, Robert Lee (J).
Summit—Winter, Henry E. (M).

New Mexico

Eunice—Tippit, Marvin Ray (A).
Hobbs—Bowen, Stanley Van (J); Ellis, John Charles (J); Engbrecht, Eric Fred (R, A); Heald, Kenneth Conrad, Jr. (M); Morrison, Miquel Henry (J); Reed, Joe D. (J).
Roswell—Fulkerson, Frederick de Boogh (M).

New York

New York—Biggerstaff, Neil Bedford (M); Docksey, Patrick (M); Keightley, Frank Geoffrey (M).
Queens Village—Anderson, William James (A).

Oklahoma

Bartlesville—Burgess, Frank Ross (M); Eng, Harvard (A); Newman, Walter Dale (J).
Cushing—Freeman, John W. (A).
Duncan—Roberts, Hayden (M).
Nowata—Wyrick, Jesse E. (R, C/S-S-J).
Oklahoma City—Ellwood, Eugene T. (M); Griswold, Fred M. (M); Henry, James Boyd (J); Randolph, Philip (A).
Ponca City—Bocquet, Philip Edmund (M); Lee, Emerson Howard (A).
Tulsa—Brinkman, Fred Hobson (R, C/S-S-J); Caldwell, Harold Leroy (M); DeVore, Stephen F. (M); Filley, Everett R., Jr. (M); Nelson, Homer Alan (M); Overhuls, Robert Long (M); Sicking, John N. (J); Stuntz, Ross Maxwell, Jr. (M); True, Harry West (M); Wallace, Robert Barnard (A).

Pennsylvania

Lewis Run—Macfarlane, Robert Marshall (M).
New Kensington—Brukner, John Shields (J).
Pittsburgh—Rosenberg, Milton (J).

Texas

Abilene—Carver, Ralph Whiteford (J); Miller, Robert E. (A).
Austin—Crawford, George Wolf (M).
Beaumont—Petuch, Boleslaw (M).
Beeville—Sanders, Raymond Phillip, Jr. (J).
Bellaire—Boudreaux, George Shelton (J); Kymen, Harvey Lee (J).
Borger—Parsons, D. Duke (M).
Corpus Christi—Hammond, Ralph Bryan (M); Mason, John Whitney (M); Parrish, Randall Johnsey (J); Patterson, Roy Davis (J).
Corsicana—Throop, William Hilliard (M).
Dallas—Elvington, Paul L. (M); Foster, James Henry (J); Jacknin, Bernard (M); Josey, Clinton Wiley, Jr. (J); Keller, Joe Henry (M); McAnnally, Norman Ray (J); McLendon, Dan Harvey (M); Miller, Frank Hampe (M); Shireman, Howard C. (M); Stansbury, Harry Nelson (M); Wahl, William Laurence (M); Wiley, Lloyd Raymond, Jr. (M); Winters, Robert Keith (M).
Denver City—Poulter, Edwin (R, C/S-S-M).
Fort Worth—Basham, Raymond Burns (M); Losher, Don Jay (R, C/S-J-M); McCleary, Henry Glen (M); Parrish, Walter James (M); Sherman, John Ralph (M).
Gladewater—Presley, Donald F. (J).
Hamlin—Ballard, James Otis (M).
Houston—Allen, Harris Hayes (M); Barton, Rowland Chatham (J); Bear, Arthur Leo (J); Boren, William Meredith (J); Boyd, William E., Jr. (J); Brown, Stephen Slade (M); Cazayoux, Francix Trudeau (J); Chance, Wallace Kent (M); Charter, Loy M. (M); Desadier, Bluford Earl (J); Durrett, John Linwood (J); Eckel, Carl Henry (M); Foreman, Arnal Bruce, Jr. (M); Foreman, Marion Albert (A); Foster, Arthur Philip, Jr. (J); Freeman, Mathew Livingston, Jr. (M); Green, Bethel Quinton (M); Haldus, Walter Joseph (M); Henry, Arthur J. (J); Hoyer, Wilmer A. (J); Kaiser, Albert Delany, Jr. (J); Killingsworth, Francis Inzer (M); Kleban, Jack Edwin (J); LeBus, Jake H. (M); Lutey, John T. (A); McDonald, Price (J); O'Neal, Billie Don (J); O'Reilly, Wallace Michael (M); Pennebaker, Eugene Strode (M); Reardon, Edwin Everett (J); Reed, Gene Russell (A); Rice, Kenneth Murray (A); Rice, Robert Jordan (M); Roome, Walter Cecil (M); Shepler, Paul Roberts (A); Sikora, Vincent John (C/S-J-M); Skipper, Uvon (J); Styles, L. D., Jr. (A); Sutton, Gary Burt (J); Terrill, Harry Burton, Jr. (J); Walker, Terry (M); Walter, Joseph Charles, Jr. (R, J); Watson, Ralph Archibald (R, M); Wood, John William (A); Wright, Marion Fendall (A).
Liberty—Berry, John Turner (R, J).
Midland—Adams, Lee Allen, Jr. (J); Baze, Roy Allen (M); Henson, George Freeland (M); Wardroup, William Richard, Jr. (M); Zeman, Paul Robert (J).
Richardson—Shepard, John Calvin (M).
Rockport—Hodges, Lester Eugene, Jr. (J).
Sugar Land—Kirkpatrick, Willard H. (M).
Wichita Falls—Armstrong, Carlie William, Jr. (M); Garland, Thomas M. (A); Krasovec, Robert Thomas (J); McCoy, Martin R. (M).

West Virginia

Charleston—Stanton, Edward Cramon, Jr. (M).

Canada

Calgary, Alta.—Franke, Calvin Leo (R, C/S-S-M); Kernahan, George Martin (M).
Edmonton, Alta.—Maneffa, Mario (J).
Toronto, Ont.—McCamus, Frank William (J).

Colombia

Bogota—Plummer, Roger Sherman, Jr. (M); Rathburn, Lloyd Calvin (M).

England

London—Davison, Kenneth Henry (M).

Iraq

Kirkuk—Blair, Kenneth (M).
Mosul—Tennant, Frank Edward (M).

Venezuela

Anaco—Grebe, Robert William (A).
Barcelona—Black, James Alexander (M); Miller, Paul Jacob (M); Wooster, Lester Arnold (M).
Caracas—Hoffman, Walter Frederick (J); Morgan, Christopher Ralph (M); Munich, Walter George (J); Young, Herbert Arthur (J).
Lagunillas—Evans, Robert Arnoux (J); Reid, Charles M., Jr. (M).
Maracaibo—Rueb, Terry Joseph (J).
Puerto La Cruz—Berry, William Granville (A); Hauteman, Jay Gordon (J).

PROFESSIONAL SERVICES

This space available only to AIME members.
Rates Upon Request

AMSTUTZ AND YATES, INC.
Petroleum Engineers and Geologists
Estimates of Oil and Gas Reserves
Property Valuations, Reservoir Analyses
Geologic Investigations
406 KFH BLDG., WICHITA 2, KANS.

E. L. ANDERS, JR.
Consulting Petroleum Engineer
Secondary Recovery
Reservoir Analyses
Oil Property Management
230 Petroleum Building
ABILENE, TEXAS
Phone: 3-2251

BALL ASSOCIATES
OIL AND GAS CONSULTANTS
Douglas Ball
Rex E. Cheek — Taber de Polo
1025 VERMONT AVENUE, N.W.
WASHINGTON, D.C.

J. HOWARD BARNETT
PETROLEUM CONSULTANT
Casper National Bank Bldg. — Phone 2-1758
113 East Second St. — Casper, Wyoming

ROBERT M. BEATTY
Consulting Geologist
Esperson Building — Houston, Texas

BERRY & PHILLIPS
Consulting Petroleum Engineers
Reserve Estimates — Economic Analyses
Management
MIDLAND, TEXAS
203 Leggett Building — Phone 2-0019
O. H. Berry — Charles E. Phillips

BRADLEY, OLIVER AND ASSOCIATES
PETROLEUM CONSULTANTS
Geology, Engineering and Management
3300 Republic Bank Bldg.
Dallas, Texas — ST-5331

Oil and Gas Reserves—Appraisals
Flooding—Technology
J. RANDOLPH BUCK
Petroleum Engineer
National City Bldg. — STerling 1688
DALLAS, TEXAS

JOHN L. JORDAN
Analytical and Petroleum Chemist
Podbielniak and Charcoal Analysis
Water - Oil Field Brines
CAMPBELL LABORATORIES
Phone: Tulip 4-0371 — Corpus Christi, Texas

CHEMICAL & GEOLOGICAL LABORATORIES
Consultants - Investigations - Evaluations
James G. Crawford ..... Petroleum Engineer
F. Raymond Wheeler ..... Petroleum Engineer
P. O. BOX 279 — CASPER, WYOMING

CRUTCHFIELD AND PRUETT
CONSULTING PETROLEUM ENGINEERS
Wilson Tower
CORPUS CHRISTI, TEXAS
John W. Crutchfield — *Horton T. Pruett*
Donald D. Lewis

EARLOUGHER ENGINEERING
Petroleum Consultants - Core Analyses
Specializing in Secondary Recovery
Investigations - Appraisals - Operations
3316 East 21st St.
TULSA 14, OKLAHOMA
Phone: 9-6345

EASTON & SACRE
Consulting Petroleum Engineers
E. M. Easton
L. P. Sacre, Jr.
H. M. Allen
1716 Oak Street — Phone FAirview 5-5026
BAKERSFIELD, CALIFORNIA

WARD M. EDINGER
Consulting Petroleum Engineer
Secondary Recovery
Oil and Gas Reserves
Reservoir Analyses
729 Hightower Building
Oklahoma City, Okla. — FO-5-1421

EMPIRE RESOURCES MANAGEMENT, INC.
Management, Consulting and Evaluation
Oil, Gas and Uranium
J. Crichton, Pres.; C. C. Harter, Jr., Vice Pres.
602 FIDELITY UNION LIFE BLDG., DALLAS
ST-5396
4TH FLOOR C&I BLDG., HOUSTON, CA-89571

FITTING & JONES
Engineering and Geological Consultants
Ralph U. Fitting, Jr.
J. R. Jones
T. W. Hassell
Petroleum — *Natural Gas*
223 S. Big Spring St. — Box 1637
Phone 4-4451 — Midland, Texas

ROBERT D. FITTING
Petroleum Consultant
Engineering and Geology
MIDLAND, TEXAS
201 West Building — Phone: 4-4922

MICHEL T. HALBOUTY
CONSULTING GEOLOGIST
AND PETROLEUM ENGINEER
Shell Building
Houston 2, Texas — Phone PR-6376

HARRELL DRILLING AND OIL COMPANY
Contract Drilling—Production
Geological Appraisals
MELROSE BUILDING
HOUSTON, TEXAS

E. W. HOUGH
Emulsion and Paraffin Problems
Box 7547 — University Station
Austin, Texas
Registered Engineer in California and Texas

KELLER & PETERSON
Petroleum Consultants
Reserve Estimates — *Reservoir Analysis*
Petroleum and Geological Engineering
902 W. T. WAGGONER BLDG.
FORT WORTH, TEXAS
Phone: FAnnin 7583
W. O. Keller — L. F. Peterson

R. W. LAUGHLIN
Well Elevations
Laughlin-Simmons & Co.
2010 S. Utica
TULSA 4, OKLAHOMA

LEIBROCK & LANDRETH
Consulting Petroleum Engineers
Valuations—Reservoir Analyses
Proration—Geological Investigations
Property Management—Well Completions
PETROLEUM LIFE BLDG.
MIDLAND, TEXAS
Phone 2-7500 — P. O. Box 605
GEORGE H. LANDRETH — *R. M. LEIBROCK*

LLOYD, PENN, HILLS & LeSASSIER
WILLIAM Y. PENN — JOHN M. HILLS
JOHN W. LeSASSIER
Geologists — Consultants — Appraisers
21 PERMIAN BLDG. — MIDLAND, TEXAS

MARTIN, WILLIAMS & JUDSON
PETROLEUM CONSULTANTS
Engineering - Geology - Management
131 Central Bldg. — Phone 2-5216
MIDLAND, TEXAS
William H. Martin — R. Ken Williams
Edward H. Judson

BUCK J. MILLER
Petroleum and Geological Engineering
Evaluations—Reservoir Analysis
Geological Investigations
917 Staley Building, Wichita Falls, Texas
Telephone: 3-9582

M. M. MONTGOMERY
CONSULTING PETROLEUM ENGINEER
Valuations, Drilling, Well Completions
Production, Workovers
Property Management
Hapip Bldg. — Williston,
3-4642 — North Dakota

NOWLAN-DODSON ENGINEERING, INC.
Reservoir Analyses - Water Flood Projects
Natural Gas Engineering
Gas Storage Reservoirs
EVANSVILLE, INDIANA
319 COURT BUILDING PHONE 5-8154

OILFIELD RESEARCH
Core Analysis Reservoir Engineering
1907 DIVISION, EVANSVILLE, IND.
Phone: GR 7-1508 (Night GR 6-0608 or GR 6-4882)
Service Laboratories
MT. VERNON, ILL. PAINTSVILLE, KY.
5131 —(Phones Day or Night)— 1160

MARK OLSON
Petroleum Consultant
Southwest Texas
202 Britton Rio Grande City, Texas

ERNEST K. PARKS
CONSULTING PETROLEUM ENGINEER
Planning, Direction and Examination of Oilfield Operations, Estimates of Oil and Gas Reserves, Oil Property Valuation
306 N. Cliffwood Ave., Los Angeles 49, California
Telephone: GRanite 2-2632

PETROLEUM CONSULTANTS
Engineering and Geology
E. O. Bennett James O. Lewis
D. G. Hawthorn M. D. Hodges
1552 Esperson Building Houston 2, Texas

PETROLEUM TECHNOLOGISTS
Production Research - Core Analysis
Secondary Recovery
868 Truckway, Montebello, Calif.
NORRIS JOHNSTON PArkview 1-5338

PISHNY AND ATKINSON
Engineers and Geologists
Valuation of Oil and Gas Properties
2412 Continental Life Bldg.
FORT WORTH, TEXAS
Chas. H. Pishny Burton Atkinson

E. E. REHN
Consulting Petroleum Geologist
Oil Exploration
Wood Building, 624 Locust Street
EVANSVILLE, INDIANA

RUSSELL ENGINEERING
PETROLEUM CONSULTANTS
WATER ANALYSTS CORE ANALYSTS
Specializing in Secondary Recovery
Registered Professional Engineers
James E. Russell P. M. Bridges
R. G. Prentice W. L. Hammer
101 Petroleum Bldg. 4-4386
ABILENE, TEXAS

R. WAYNE RUSSELL
PETROLEUM CONSULTANT
Engineering and Geology
DALLAS, TEXAS
625 Reserve Loan Life Building
Phone ST-3020

JOHN HOWARD SAMUELL
Specializing in Bank Valuations
Geologist and Petroleum Engineer
Compton Building Box 732
Phone 4-4493 and 4-4597, Abilene, Texas

WM. H. SPICE, JR.
Consulting Geologist
2101-03 Alamo National Building
SAN ANTONIO 5, TEXAS

SUBSURFACE ENGINEERING COMPANY
Experts in Field Testing, Sampling and Analyzing Reservoirs and Reservoir Fluid for Reservoir Studies
WRIGHT PETROLEUM LABORATORY
Home Office: Box 1827, Tulsa
Frank Purdum

CHARLES C. WILLIAMS
WILLIAMS SEISMOGRAPH, INC.
Consulting Geophysicists
252 South Green St. MUrray 2-7275
WICHITA, KANSAS

PRIMARY AIDS FOR SECONDARY RECOVERY OPERATIONS

TRETOLITE COMPANY'S

KONTOL *corrosion inhibitor*
X-CIDE *bactericide*

KONTOL

KONTOL Corrosion Inhibitor effectively prevents corrosion damage in water supply wells, injection wells, pumps, meters and internal pipe surfaces in the water flood system. Kontol Corrosion Inhibitor also lowers water-oil interfacial tension, a property often desirable in water flooding operations.

X-CIDE

X-CIDE Bactericide prevents the growth of anaerobic and aerobic micro-organisms in both fresh and salt water systems. It destroys the organisms which convert sulfates to hydrogen sulfide. Hydrogen sulfide not only is highly corrosive, but also causes soluble iron to precipitate as insoluble iron sulfide, which plugs injection formations.

For complete information on Tretolite Company products and services for secondary recovery applications, ask your Tretolite Field Engineer, or write to

TRETOLITE COMPANY
A DIVISION OF PETROLITE CORPORATION
369 MARSHALL AVENUE, ST. LOUIS 19, MISSOURI
5515 TELEGRAPH ROAD, LOS ANGELES 22, CALIFORNIA

Specialized Chemicals and Services for the Petroleum Industry

DEMULSIFICATION • SCALE PREVENTION
PRODUCTION STIMULATION • DESALTING
CORROSION INHIBITING • BACTERICIDES
PARAFFIN REMOVAL • WATER DE-OILING

B 5520

Formation Evaluation Symposium in Houston Attended by 1,300 Persons

Approximately 1,300 persons attended the two-day Formation Evaluation Symposium in Houston on Oct. 27-28. The meeting was sponsored jointly by the Gulf Coast Section of AIME, University of Houston Student Chapter of AIME, and the Dept. of Petroleum Engineering of the University of Houston. Technical sessions were held on the University of Houston campus.

Registrants for the meeting received a 208-page bound volume on formation evaluation techniques. This volume was composed of 14 papers which were presented on the two-day program. Copies of this volume may be obtained from the Gulf Coast Section of AIME for $5.00.

The Symposium was the culmination of a Gulf Coast Local Section of AIME Study Group series on Formation Evaluation. J. D. Clark, Union Oil Co. of California, was chairman of the Symposium Committee, and C. V. Kirkpatrick was the program chairman.

Now Available

Formation Evaluation Symposium Volume

- A 208-page bound volume of papers presented at the Gulf Coast Section of AIME Formation Evaluation Symposium.
- Designed to provide complete coverage of present-day formation evaluation techniques.
- Includes 14 papers, complete with illustrations:
  - *Formation Evaluation of Oil and Gas Reservoirs*, by Norman J. Clark and H. M. Shearin, Core Laboratories
  - *Fundamental Theory and Instrumentation of Electrical Logging*, by I. L. Roberts, Schlumberger Well Surveying Corp.
  - *The Fundamentals of Quantitative Analysis of Electric Logs*, by R. H. Winn, Halliburton Oil Well Cementing Co.
  - *Electrical Logging Interpretation in the Gulf Coast*, by M. P. Tixier, Schlumberger Well Surveying Corp.
  - *The Theory and Instrumentation of Radiation Logging*, by E. R. Atkins, Jr., Union Oil Co. of California
  - *Mud Analysis Logging and Its Use in Formation Evaluation*, by R. W. Wilson, Baroid Div., National Lead Co.
  - *The Fundamental Principles of Core Analysis and Their Application to Gulf Coast Formations*, by Ben A. Elmdahl, Houston consultant
  - *A Review of Drill-Stem Testing Techniques and Analysis*, by W. Marshall Black, Humble Oil & Refining Co.
  - *Formation Evaluation of Felix Jackson No. 40 Well, Frio Formation, Oyster Bayou Field, Chambers County, Tex.*, by C. R. Glanville, Sun Oil Co.
  - *Formation Evaluation in the Seeligson and Borregos Fields*, by Harold T. Wright and L. D. Wooddy, Jr., Humble Oil & Refining Co.
  - *Formation Evaluation of Some Limestone Reservoirs With Particular Reference to Well Logging Techniques*, by E. E. Finklea, Amerada Petroleum Co.
  - *Well Logging Study—Quinduno Field, Roberts County, Texas*, by Joe D. Owen, Phillips Petroleum Co.
  - *Petrophysical Analysis of Some Wilcox Wells*, by S. M. Paine, Shell Oil Co.
  - *An Integrated Summary of Formation Evaluation Criteria*, by C. V. Kirkpatrick, University of Houston
- Copies of the volume may be obtained from: H. M. Krause, Humble Oil & Refining Co., Box 2180, Houston, Tex.

Price: $5.00

Texas A&M Chapter Elects Officers

Junior class officers have been elected for the Petroleum Engineering Club of Texas A&M. They are: Harry Piper, secretary; Buddy Byrne, treasurer; George N. Manitzas, reporter; and Bill Tom, junior representative to the Engineering Council.

The president, Dick Durbin, and vice-president, Bob Scarbrough, had been elected to office last spring. Special guest of the Petroleum Club at the organizational meeting was John C. Calhoun, Jr., new A&M Dean of Engineering. Others present included R. L. Whiting, Bill Amyz, John Pedigo, Dan Bass, and Harvey T. Kennedy.

Tom Irby was the featured speaker for this meeting, talking on "First Year's Experience in the Field." He is a 1954 graduate of Texas A&M now doing graduate work.

NEW FORT WORTH OFFICERS

New officers for the Fort Worth Local Section were elected at the October meeting of this group. They are, left to right: R. E. Kellerman, Texas Crude Co., secretary-treasurer; Bruce E. DeBrine, Pure Oil Co., fourth vice-chairman (statistics); L. W. Folmar, The Texas Co., chairman; H. A. Metzger, Lane-Wells Co., first vice-chairman (program); T. W. Painter, Welex Jet Services, third vice-chairman (membership); and Lewis H. Bond, Jr., Fort Worth National Bank, section delegate.

Registration Is 678 for Annual Southern California Fall Meeting

The Southern California Petroleum Section Fall Meeting attracted 678 persons. This meeting was held in the Biltmore Hotel, Los Angeles, on Oct. 20-21.

Included in the total registration were 142 engineers who attended the Mining Branch and Metals Branch activities. Highlights of the meeting were talks by Robert B. Gilmore, Petroleum Branch chairman, and Harrison S. Brown, California Institute of Technology. Gilmore spoke at a Thursday luncheon; Brown spoke Friday at a luncheon.

At the Petroleum Section Luncheon and Annual Business Meeting, Gilmore told of the progress of the Petroleum Branch in 1955. Officers of the Southern California Petroleum Section for 1956 were nominated. Election will be made by a letter ballot.

At the All-Sections Luncheon Brown spoke on "The Future of the World's Mineral Resources." He is professor of geochemistry at California Tech.

Preprints of papers presented at this meeting may be obtained for $3.00 per set from M. Boyd McCoy, Halliburton Oil Well Cementing Co., 1709 W. 8th St., Los Angeles 17, Calif. A list of all 20 papers presented there was included on pages 36 and 37 of the October issue of JOURNAL OF PETROLEUM TECHNOLOGY.

General chairman for the meeting was Sam Grinsfelder, Union Oil Co. of California. Floyd E. Schoonover, Monterey Oil Co., was program chairman. Although referred to as the Southern California Petroleum Section Fall Meeting, the event was co-sponsored by the San Joaquin Valley Section of AIME.

West Virginia Chapter Holds Meeting

The AIME Student Chapter of West Virginia University held its first meeting on Oct. 12. Successive meetings are scheduled for the second Wednesday of each month, and they will feature speakers from industry.

Officers for the 1955-56 school year are: Michael Ruppert, president; Alfred Cogbill, vice-president; Paul Weigmann, secretary-treasurer; and Professor R. W. Laird, faculty advisor.

MEET the AUTHORS

REX E. CHEEK was graduated from the Colorado School of Mines with the degree of petroleum engineer in 1943 and later received his MS in petroleum engineering from the University of Oklahoma. He was employed by Stanolind Oil and Gas Co. as a petroleum engineer, served with the Marine Corps during World War II and is now associated with Ball Associates, Oil and Gas Consultants, Washington, D. C.

D. E. MENZIE is an associate professor of petroleum engineering at the University of Oklahoma. He is at present on a year's leave of absence to continue graduate study. He previously taught at the Pennsylvania State University for two years and was employed for three years by Pennsylvania Grade Crude Oil Assn. He holds BS and MS degrees from Pennsylvania State University and is national executive secretary to Pi Epsilon Tau, petroleum engineering honorary society.

G. J. HARMSEN was graduated from the "Vrije Universiteit" at Amsterdam in 1952. He joined the staff of the Koninklijke/Shell (Royal Dutch/Shell) Laboratory at Amsterdam as a physico-chemist and at present is working on reservoir-engineering problems.

J. L. HUITT is a senior research chemical engineer at Magnolia Petroleum Co. Field Research Laboratories, Dallas. He has been with Magnolia since 1951, now working in the Wellbore Mechanics Activities of the Production Research Div. Huitt holds a BS degree in chemical engineering from Louisiana Tech and MS and PhD degrees in this field from University of Oklahoma.

PAULO VARJÃO DE ANDRADE received his BS degree from the School of Chemistry of the University of Brazil. He joined the Brazilian National Petroleum Council in 1947 and spent 1952 in the United States as a Point Four trainee working at the U. S. Bureau of Mines Station in Bartlesville. Now, he is in charge of Petrobras laboratory in the State of Bahia.

H. C. LEFKOVITS holds a research contract with the operations analysis department of Shell Development Co. and at present is attending Rice Institute in preparation for his PhD degree in mathematics. He received his BA degree in mathematics and MA degree in physics from the University of Texas.

(Continued on Page 40)

REAL EVIDENCE
B and W Scratchers remove mud cake, and here is how to prove it
1. Run B and W Scratchers on your casing.
2. Move the casing after it reaches bottom.
3. Circulate until returns from bottom reach the shaker screen.
B and W LATCH-ON CENTRALIZER
B and W Nu-Coil Scratcher
B and W MULTI-FLEX SCRATCHER
B and W Rotating Scratcher
THERE IT IS! . .
You will see all the evidence you need to convince you that B and W Scratchers and Centralizers have conditioned the hole . .
For a GOOD CEMENT JOB

B and W Inc.
Well Completion Specialists

GULF COAST
Box 5266
Houston 12, Texas
Phone WA-3-6603

WEST COAST
Box 3751
Los Angeles 54, Calif
Phone DA-4-1106

MEET THE AUTHORS

(Continued from Page 39)

A picture and biographical sketch of CHARLES S. MATTHEWS were published in the October, 1955, issue of JOURNAL OF PETROLEUM TECHNOLOGY.

JIM DOUGLAS, JR. received his BS and MS degrees in civil engineering from the University of Texas and MA and PhD degrees in mathematics from Rice Institute. He taught engineering mechanics at the University of Texas and later joined the Production Research Division of Humble Oil & Refining Co. in 1952.

D. W. PEACEMAN joined the Production Research Division of Humble Oil & Refining Co. in 1951 and has been working in the field of application of mathematics to the solution of reservoir engineering problems. He has a BChE degree from the College of the City of New York and a ScD degree in chemical engineering from M.I.T.

NECROLOGY

Elected	Name	Date of Death
1934	R. E. Heithecker	Oct. 20, 1955
1955	P. Ross Pratt	Sept. 16, 1955
1947	Joseph G. Wilson	Aug., 1955
1955	Lynn D. Speer	Sept. 15, 1955

H. H. RACHFORD, JR. has a BS degree in chemical engineering and MS degree in physical chemistry from Rice Institute and a ScD from M.I.T. He has been associated with Humble Oil & Refining Co. in the Production Research Division since 1949.

A. S. MURRAY received his BS degree in petroleum engineering from the University of Tulsa in 1948. After graduation he joined the Venezuelan Atlantic Refining Co. Later he joined Imperial Oil Limited to set up a new section concerned with drilling engineering research and problems and is now regional drilling engineer in Imperial's Producing Dept. at Calgary, Alberta, Canada.

R. A. CUNNINGHAM is a project engineer in the Research Engineering Dept. of the Hughes Tool Co. He holds BS and MS degrees in mechanical engineering from Rice Institute. Cunningham has been associated with Hughes Tool Co. since 1949. In 1953 he transferred to the Hughes Research Engineering Dept.

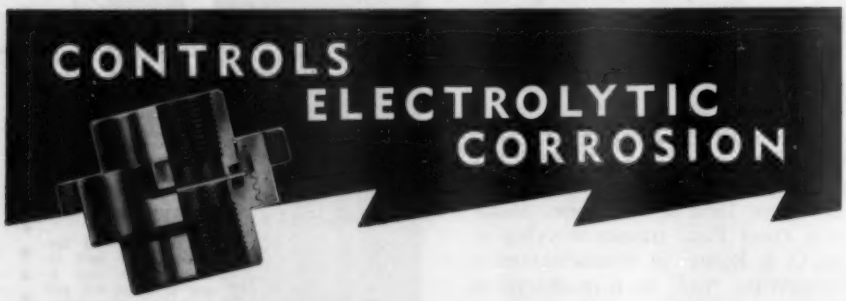


FIGURE 110 INSULATED UNIONS prevent electrolytic corrosion by breaking the flow of electrolytic current. Non-metallic, non-conductor gaskets separate the metal parts of the union . . . stop the passage of current through the line. Gasket material is very dense and has high compressive strength, is impervious to seepage and wholly resistant to oil and common acids. Use FIGURE 110 INSULATED UNIONS on Christmas Trees, flow lines, manifolds and other piping systems for maximum protection at lowest cost. Furnished in sizes from ⅛" through 6", working pressures to 3000 psi. YOUR SUPPLY STORE CAN FURNISH ALL SIZES.

YALE MACHINE WORKS
BOX 10117 • HOUSTON, TEXAS
Distributed By
YALE SALES COMPANY
P O BOX 10192 • HOUSTON, TEXAS • TELEPHONE ME-5-6418

WHAT'S NEW IN TEXAS?

NEW SOURCE OF Lithium Hydroxide

The new $6,600,000 plant of American Lithium Chemicals, Inc. in San Antonio, an affiliate of American Potash & Chemical Corporation, long the leading producer of Lithium Carbonate, makes available to producers of lithium-based greases an abundant new source of supply of LITHIUM HYDROXIDE. The new plant will process high-grade lithium ores from extensive deposits in Southern Rhodesia, assuring you of vast reserves, coupled with the most modern domestic production facilities available anywhere. You can count on the advantages of Trona LITHIUM HYDROXIDE in your all-purpose greases—moisture resistance, chemical and mechanical stability and wide temperature range, just as you can depend on the consistent good quality of Trona's new source of this vital all-purpose, all weather grease additive.

Send for technical information sheet

FOR *Producers of*
LITHIUM-BASED GREASES

FOR LITHIUM CHEMICALS—LOOK TO AMERICAN POTASH!

TRONA
INDUSTRIAL AND AGRICULTURAL CHEMICALS
ESTON CHEMICALS

American Potash & Chemical Corporation

Offices • 3030 West Sixth Street, Los Angeles 54, California
• 99 Park Avenue, New York 16, New York
• 214 Walton Building, Atlanta 3, Georgia
Plants • Trona and Los Angeles, California and San Antonio, Texas
Export Division • 99 Park Avenue, New York 16, New York

LITHIUM CARBONATE • LITHIUM HYDROXIDE • LITHIUM BROMIDE • LITHIUM CHLORIDE and other LITHIUM CHEMICALS

Buzzalini New Secretary of Mining Branch, AIME

After several months' search, during which more than 40 men were considered for the job, Arnold Buzzalini has been engaged as the new secretary for the Mining Branch of AIME.

Buzzalini most recently has been manager and chief geologist of the Uranium Div. of Pubco Development, Inc., Albuquerque. He has also been secretary of the New Mexico Geological Society and was chairman of the committee for its ninth annual meeting in Gallup last May.

Arnold, or "Buzz," comes from a mining family—his father, grandfather, and uncles all having worked for the Colorado Fuel and Iron Co. He received his BS degree in the Syracuse University Dept. of Geology, and later did graduate work at Johns Hopkins and Penn State.

In 1951 he worked for a year with Phillips Petroleum Co. as a staff geologist on exploration and development. Last year he joined the company's Strategic Minerals Div., and a few months ago he accepted a position with Pubco.

Arnold's hobbies are hunting, fishing, pistol marksmanship, gem and mineral collecting and polishing, photography, skiing, and Boy Scout work. At college he earned his letter in boxing, fencing, and rifle shooting, having received the 1942 Intramural Managers Medal. At that time he was a Student Associate of AIME.

The 32-year-old secretary has written several papers on geological subjects, some of which he presented at society meetings.

Since C. M. Cooley gave up the secretaryship of the Mining Branch last February to devote his full time to the editorship of Mining Engineering, E. H. Robie has been acting-secretary of the Branch.

Another industry standard established first by Baroid

The unseen staff that rides with your Baroid engineer

There is a staff of unseen riders in the familiar field car of every Baroid mud engineer. Their knowledge and experience help him work quickly and surely to bring success to your drilling. The man you see has experience in your locality through his own work, his District Superintendent, his Area Engineer, and more than a half-million well reports on tap at the home office.

Since mud engineering began — and it began with Baroid — these men are constantly improved through never-ending training from the Baroid technical school. To this skill are added the results of mobile laboratory tests, the findings of the unequalled mud service laboratories, and the guidance of new product research. All of this knowledge is focused on your mud program through the Baroid man at your well.

The results for you are an end of mud troubles, faster and more economical drilling, and better completions. No other mud company can match the extensive facilities that back up your Baroid engineer. Call him today.

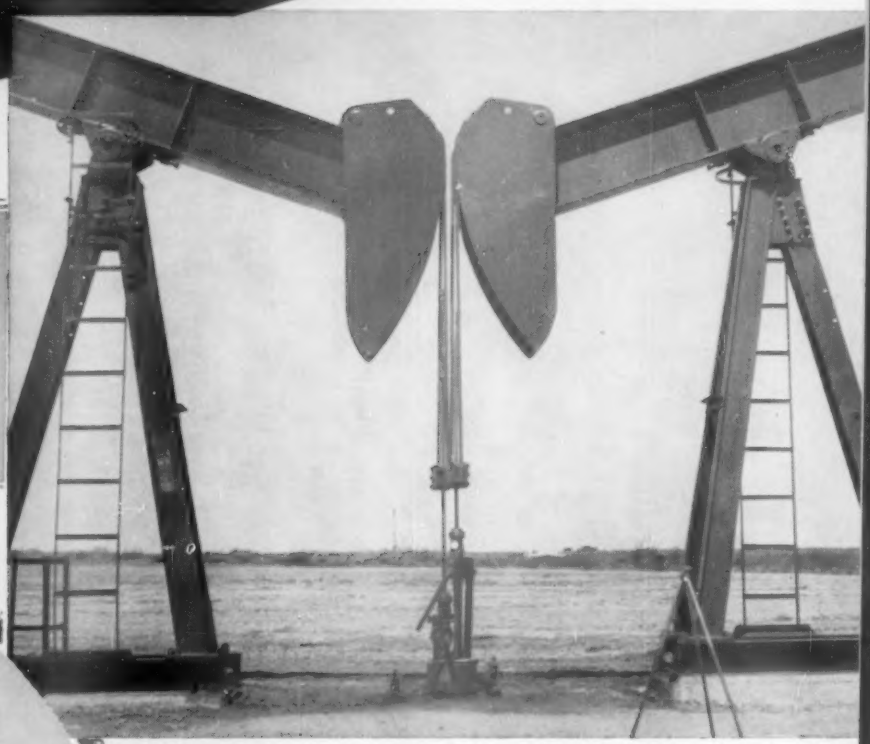
Mobile research units tackle toughest problems.
Service laboratories give immediate aid.
Product development tests newest ideas.
Continuous training in latest mud techniques.
Research labs for new and improved technology.
More than 2,400 man-years of Baroid experience available.
Case history files on over a half-million mud tests.
BAROID

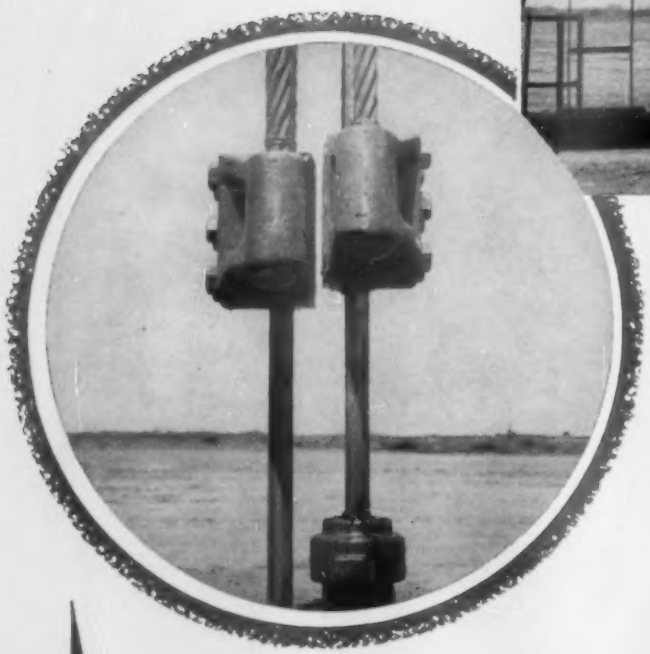
BAROID DIVISION • NATIONAL LEAD CO.
Main Office: P. O. Box 1675, Houston 1, Texas

5037

two LUFKINS get their HEADS together

to solve another "Knotty" dual completion pumping problem





New LUFKIN "Flush Type" hanger bar with built-in polished rod clamp makes possible the operation of two strings on as close as 3¾ inch centers.

◀ TWO ZONES PRODUCED INDEPENDENTLY IN ONE WELL BY THE USE OF TWO PUMPS WITH SEPARATE STRINGS OF TUBING AND RODS.

LUFKIN FOUNDRY & MACHINE COMPANY

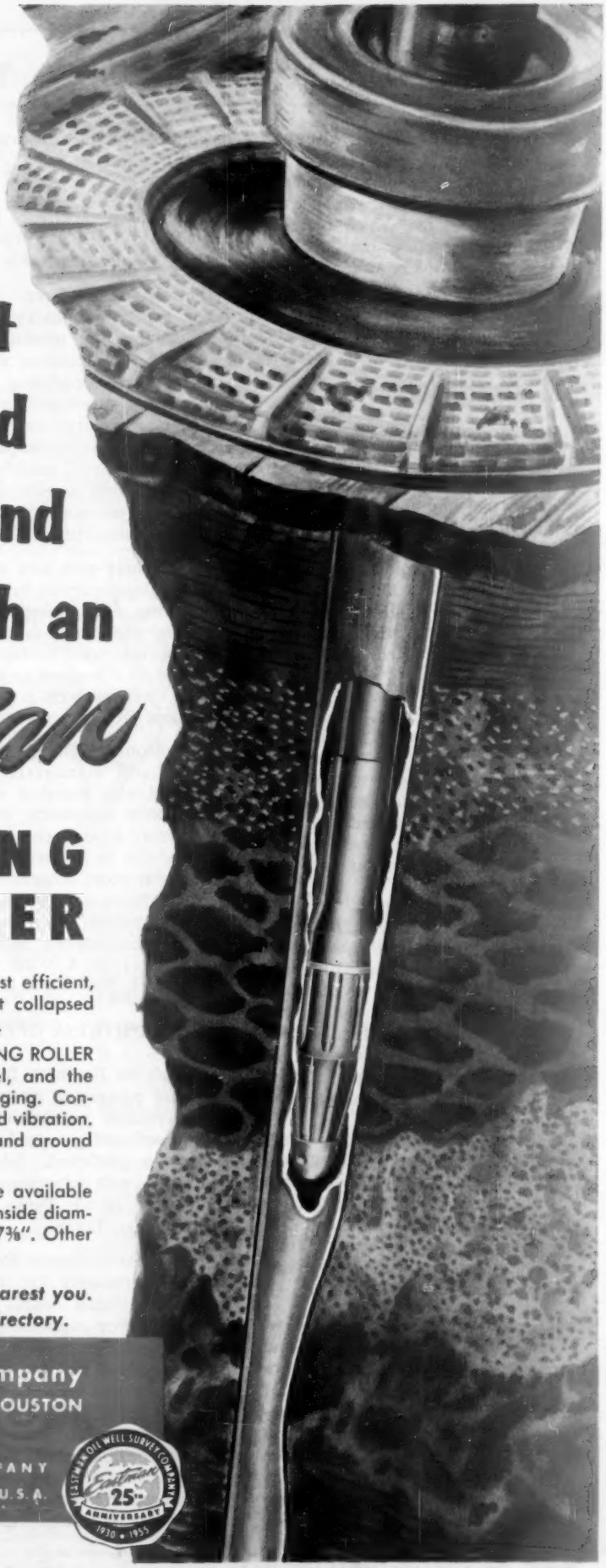
LUFKIN, TEXAS

Branch Sales and Service: Houston • Dallas • New York • Tulsa • Los Angeles • Seminole • Oklahoma City • Corpus Christi • Odessa • Kilgore • Wichita Falls • Casper, Wyoming • Great Bend, Kansas • Effingham, Illinois • Sterling, Colorado • Lafayette, Louisiana • Bakersfield, California • El Dorado, Arkansas

Lufkin equipment in Canada is handled by THE LUFKIN MACHINE CO., LTD., 14321 108th Avenue, EDMONTON, ALBERTA, CANADA

Roll out collapsed casing and liners with an

Eastman CASING ROLLER



The Eastman CASING ROLLER is the most efficient, effective and economical way to roll out collapsed casing and liners to their original gauge.

The body and rollers of the Eastman CASING ROLLER are made of specially heat treated steel, and the roller ends are tapered to prevent snagging. Continuous rolling surface minimizes friction and vibration. There is also circulation through the tool and around each roller.

These CASING ROLLERS are available in API sizes for casings with inside diameters ranging from 2½" to 17⅜". Other sizes made to order.

Call the Eastman office nearest you. Consult your telephone directory.

DIRECTIONAL DRILLING Eastman OIL WELL SURVEYS

Eastman Oil Well Survey Company

LONG BEACH • DENVER • HOUSTON

Export Sales and Service:

EASTMAN INTERNATIONAL COMPANY

P. O. Box 1500 • Denver, Colorado, U.S.A.

EASTMAN OIL WELL SURVEY COMPANY Eastman 25th ANNIVERSARY 1930 • 1955

EMPLOYMENT NOTICES

The JOURNAL OF PETROLEUM TECHNOLOGY will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 800 Fidelity Union Bldg., Dallas 1. These replies will be forwarded unopened and no fees are involved.

PERSONNEL AVAILABLE

☆ Registered Chemical Engineer, 43, married, two children. Ten years in drilling mud and fluid flow research. Background of physical metallurgy and physical and non-destructive testing and inspection. Looking for an opportunity to combine oilfield, research, and metallurgical experience. West Coast preferred. Now employed. Code 258.

☆ Petroleum Engineer, BS degree, 27, single. Three years' practical experience in drilling and two years as a production engineer with experience in workovers and well completions. Currently employed with major company. Desires staff position with smaller organization in South Texas. Code 262.

☆ Registered Petroleum Engineer. Experience consists of three years' drilling and production, 10 years' reservoir engineering, valuations, secondary recovery, oil and gas reserves, unitization, and regulatory commission work in supervisory assignment; Northwest Texas. Desire employment with Independent. Present salary $12,000. Code 263.

☆ Chemical-Petroleum Engineer with 10 years' experience in technical phase of oil and gas production desires responsible position with oil company or oil well service company. Any location within the U.S.A. considered. Code 264.

☆ Petroleum Engineer with 15 years' excellent experience in domestic and foreign oil production covering both planning and operational phases of primary and secondary recovery. Positions held include assistant division reservoir engineer, chief petroleum engineer major producing company. Degree in geology. Desires affiliation with sound organization able to offer responsibility and opportunity for growth. Code 265.

☆ Reservoir Engineer with six years' Permian Basin experience desires to relocate with Independent in the Dallas-Fort Worth area. Code 266.

☆ Petroleum Engineer, 36, four years' experience Rocky Mountain area drilling and production. Specialty is well completions, workovers, and design of producing facilities. Three years' experience in reservoir engineering, reserve estimates, and cost studies. Presently employed with major company. Desires position with smaller organization. Capable of managing operations or organizing engineering department. Code 267.

☆ Young man with four and a half years' college training in petroleum engineering and geology with four summers' experience in roustabouting, reservoir and production geology, desires a position in the southwest or midwest with a growing independent producer. Code 268.

☆ Petroleum Engineer with engineering and managerial training combined with practical waterflood development experience, and having had 5 years' experience with successful producer in Pennsylvania and 3 years' with major company in Southwest, desires to affiliate with a growing independent. Code P-12. Send replies to Engineering Societies Personnel Service, 8 West 40th St., Room 1207, New York 18, N. Y.

POSITIONS OPEN

☆ Petroleum Engineer for production and processing equipment design. Research possibilities. Experience in oil and gas production and processing preferred. Salary commensurate with experience. Replies confidential. Sivalls Tanks, Inc. Box 1152, Odessa, Texas.

☆ Petroleum Engineers. Experienced graduate engineers for immediate openings in Saudi Arabia and New York City. For engineering work in development, production, drilling, process and oil and gas engineering on primary and secondary recovery problems.

Supervisory Petroleum Engineer. For responsible staff position in Saudi Arabia, directing the work of experienced engineers, making petroleum reservoir studies. Advise management on petroleum reservoir engineering problems. Salary commensurate with training and experience. Write, giving full particulars regarding history and work experience: H. G. Heinze, Arabian American Oil Co., 505 Park Avenue, New York 22, New York.

☆ Research mathematician or theoretical physicist. Major oil company research laboratory has opening for PhD or MS in the field of reservoir engineering research. Previous experience in applied mathematical research desirable but not necessary. Excellent working environment with opportunities for advancement. Replies confidential. Send detailed education and experience record, age, and state salary expected. Code 590.

☆ Major independent has an opening for a petroleum engineer trainee. No previous experience necessary. Good working conditions with excellent opportunities for advancement. Replies will be considered confidential. Code 591.

☆ Financial institution seeks graduate Petroleum Engineer with several years' experience in the field and some experience in valuation of oil and gas reserves, principally in Texas and adjoining states. Position offers experience in appraising oil and gas properties, and financing in the petroleum industry. State age, education, experience, marital status, and minimum salary acceptable. Position requires some traveling from central location. Please send passport-size photo. Code 592.

☆ Leading Texas bank has unusual opportunity for outstanding reservoir engineer. Excellent salary and working conditions. BS or MS in P.E., three-five years' experience, including field work and reservoir engineering. Write giving details of academic and professional experience. Replies strictly confidential. Code 593.

☆ Designer, mechanical graduate, with oil refinery experience, for design and layout of oil and gas processing equipment. Location, northern Texas. Code W2131. Reply: Engineering Societies Personnel Service, 8 West 40th St., Room 1207, New York 18, N. Y. The ESPS collects a fee from applicants actually placed.

DUAL CIP RECORDED BY RELIABLE BOURDON TUBE

Big New Reason Why HALLIBURTON'S Best In Drill Stem Testing

Old "Reliable" has a new use for reservoir evaluation. The Bourdon Tube gauge with its extreme accuracy and sensitivity, is the most precise recording device for Dual Closed In Pressure—an important new technique in Drill Stem Testing.

When the testing tool is opened into an air chamber of a predetermined volume, the expansion chamber permits release of the hydrostatic mud pressure. Then, by a limited amount of formation production, an Initial Closed In Pressure build-up curve is recorded. The build-up curve can be mathematically extrapolated to obtain static formation pressure.

Upon completion of the Initial CIP period, the auxiliary valve is opened to produce as on a *normal* Drill Stem Test. When the flow period is completed, a Final CIP is taken by closing in the formation with the packers still seated, permitting the formation to continue to produce—thereby recording a pressure build-up curve. The Testing Chart is given special reading. The reading and chart are then reproduced and mounted into a "Formation Testing Service Folder." Some important uses which have evolved from this data are:

A. *Static Formation Pressure*

B. *Effective Permeability of the Zone Tested*

C. *Skin Effect or Damage Factor*

D. *Production Indices on Flowing Wells*

Because it's the most precise recording device, Halliburton's Bourdon Tube gauge can be relied upon as a great aid in reservoir evaluation. Use it to more accurately evaluate your well. Phone your local or district office of the Halliburton Oil Well Cementing Company.

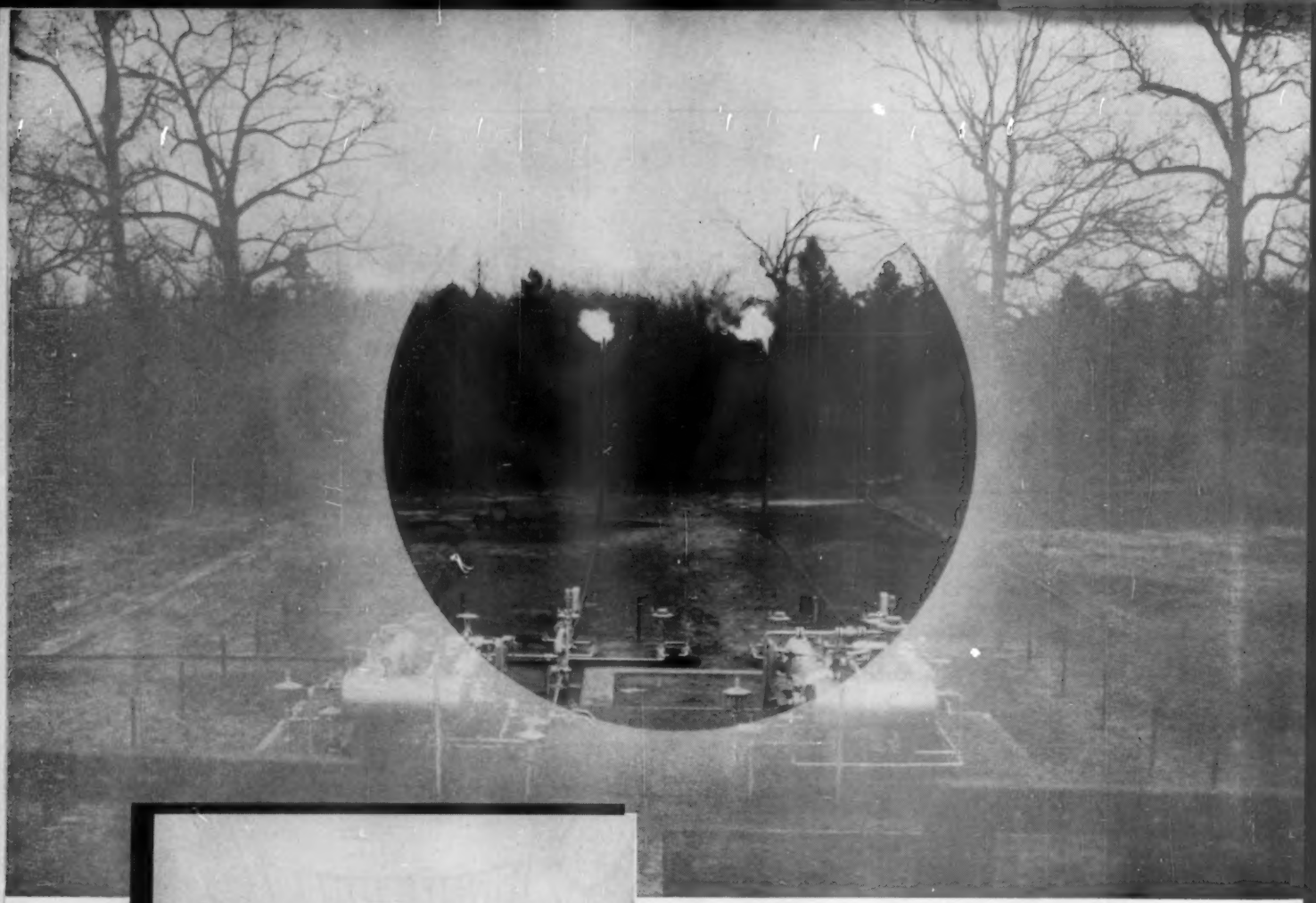
COMPLETE DATA SENT ON REQUEST

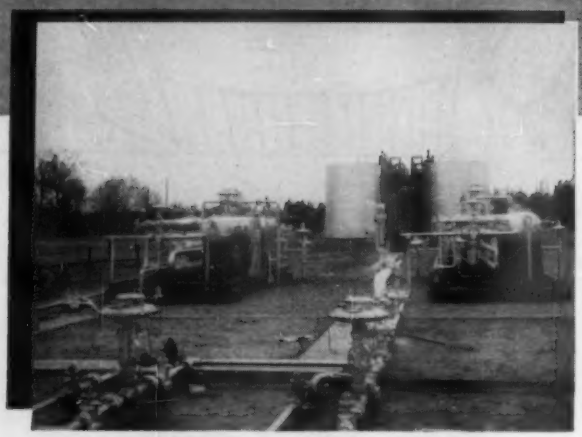
Get this valuable information for your Halliburton Service File

HALLIBURTON

TESTING SERVICE

250 SERVICE CENTERS—JUST MINUTES AWAY FROM ANY RIG





FLARE GAS
(RESERVOIR DOLLAR)
WASTE IS HELD TO THE MINIMUM WITH

National "LTX*" Systems

Heat in base of "LTX" Separator gives advantages NOT obtained by use of "LTG" (Low Temperature Glycol) Separator with no heat in base.

1. LTX means maximum high pressure gas sale, minimum low pressure gas waste, and maximum stock tank liquid recovery per unit volume of well effluent produced.
2. LTX means ability to operate without glycol injection.
3. LTX means ability to operate with glycol injection at minimum cost.
4. LTX means proven maximum trouble-free operation for all conditions and locations.

*T. M. Reg. U. S. Pat. Off.

It's a National®

NATIONAL TANK COMPANY

TULSA, OKLAHOMA

TECHNICAL NOTE 316

FLUID MAPPER MODEL STUDIES of MOBILITY RATIO

REX E. CHEEK
DONALD E. MENZIE
MEMBERS AIME

BALL ASSOCIATES
WASHINGTON, D. C.
PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PA.

ABSTRACT

The fluid mapper, a model relatively new to the petroleum industry, was used to study the effect of various mobility ratios on the areal sweepout efficiency for two typical spacing patterns. The experiments indicated the areal sweepout for the five-spot pattern varied from 51.8 per cent at a mobility ratio of 0.093 to 89.1 per cent for a ratio of 24.4. In the direct line-drive pattern, the areal sweepout varied from 58.7 per cent at a mobility ratio of 0.089 to 92.0 per cent at a ratio of 24.8. The fluid mapper may prove useful to determine quickly the effective areal sweepout for any well spacing.

INTRODUCTION

The effect of the mobility ratio on the areal sweepout efficiency during primary depletion of a water drive reservoir and during secondary recovery operations has recently become more widely recognized.[2,11,14] The mobility ratio, M, is defined as:

$$M = \frac{k/\mu \text{ (displacing fluid)}}{k/\mu \text{ (displaced fluid)}}$$

where
k = effective permeability
μ = viscosity

When the displacing fluid is miscible with the displaced fluid, the permeabilities are equal and the mobility ratio may be expressed as a ratio of viscosities:

$$M = \frac{\mu \text{ (displaced fluid)}}{\mu \text{ (displacing fluid)}}$$

The mathematical analysis for calculating the areal sweepout efficiency with mobility ratio other than unity is quite tedious.[5,11] An experimental method by using a potentiometric model[2] in a step-wise manner and in using an X-ray shadowgraph model[3,13] with continuous fluid flow has been published.

Several types of models have been used to study oil and gas reservoir performance. These models may be classified as physical, electrolytic, potentiometric, X-ray shadowgraph, and fluid mapper. The X-ray shadowgraph and fluid mapper are models relatively new to petroleum engineering and have not been used extensively for specific applications.

The theory of the fluid mapper indicates it may be adapted to a study of areal sweepout efficiencies for various mobility ratios as well as other complex problems in petroleum engineering. The use of the model and results obtained when using displacing and displaced fluids of equal densities but different viscosities are discussed.

FLUID MAPPER DEVELOPMENT

H. S. Hele-Shaw[6] developed a fluid mapper model based on the hydrodynamic theory. This theory is that in the steady flow of a viscous fluid between horizontal parallel plates spaced a very small distance apart, the effect of viscous shear is of such magnitude in the vertical plane that the motion in the horizontal plane is practically undistorted streamline flow. Techniques developed by Hele-Shaw were not expanded and no additional developments in fluid mapper models were forthcoming until A. D. Moore, University of Michigan, published a series of papers starting in 1949, which describe the construction of a flexible and inexpensive model[7,8] and the fluid mapper technique for the solution of certain problems.[9] The essential components of the fluid mapper as developed by Moore are:[7,10]

1. A base slab, made of dental stone (calcium sulphate and water), which is shaped to represent the prototype.

2. Plate glass slightly larger than the slab and spaced

Original manuscript received in Petroleum Branch office on June 9, 1954. Revised manuscript received Sept. 9, 1955.
[2]References given at end of paper.

above and parallel to the slab by means of uniformly thin spacers.

3. One or more small, movable containers and rubber tubing to supply fluid to the inlets and outlets of the base slab.

4. Crystals of methylene blue, potassium permanganate or bottles of food color for dyes to make the flow patterns visible.

5. Tray for immersing the base slab and plate glass in fluid.

EXPERIMENTAL SET-UP AND PROCEDURE

Partially scaled fluid mappers were operated to evaluate the effects on areal sweepout efficiencies when the mobility ratio was other than unity for a quadrant of a five-spot pattern. They were also operated for an element of a direct-line drive pattern in which the ratio of $b/a = 2$, where, a equals the distance between two adjacent injection wells or two adjacent production wells, and b equals the distance between the injection and production wells.

The procedure followed in building the models was essentially the same as presented by Moore and is not repeated here. Construction of the slab is relatively easy. The base slab may be cast and a single run made in a few hours. The slab is placed in the tray which contains sufficient tap water to cover the top of the plate glass when it has been placed in position. Supply tanks are then connected to the model with the rubber tubing, filled with dyed injection fluid, and the air purged from the connectors. Discharge tanks are connected and purged similarly. Brass washers ground to the desired thickness of the flow space (0.03 to 0.04 in. inclusive) are either placed on the slab in areas which will not affect the flow pattern or are placed on posts which are set up outside of the boundary of the slab. If the posts are used, it is necessary to use a second piece of plate glass for a base in the immersing tray in order to insure a uniform flow space.

A uniform flow space of 0.04 in. was used in all models for this investigation. Barriers for the boundary of the flow space were formed from molding clay. Methocel,* a water soluble cellulose ether, was used to prepare fluids of different viscosities. A 2 per cent by weight aqueous solution of Methocel 1,500 cp produces a fluid with a viscosity of approximately 1,500 cp at 20° C which may be diluted to any desired lower viscosity.[1]

Base slabs for the quadrant of the five-spot pattern were constructed with over-all dimensions of ⅞ in. x 10 in. x 10 in. Two ⅛ in. diameter wells were located at opposite corners of a square 8¼ in. in length. The direct line-drive models were constructed with the base slab having over-all dimensions of ⅞ in. x 11 in. x 19 in. The two ⅛ in. diameter wells were located 16½ in. apart on the center-line through the length of the base slab.

Constant flow rates through the models were maintained by connecting a Zenith pump in the flow system with the input port of the pump connected to the output wells in the model. The output port of the pump was connected to the input wells in the model. The Zenith pump was driven by a variable-speed Graham transmission which was connected to a Zero-Max torque converter. The Zero-Max was driven by a 1/10-hp electric motor. A schematic diagram of the model

*Registered Trademark, Dow Chemical Co., Midland, Mich.

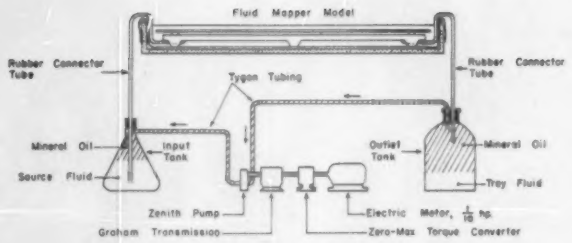


FIG. 1 — EXPERIMENTAL SET-UP.

set-up is shown in Fig. 1. Photographic records of the flow patterns were obtained with an ordinary camera mounted directly above the fluid mapper model.

RESULTS

Tests were conducted with a viscosity ratio, $M = 1$, and a fixed barrier enclosing the flow area to determine whether or not the fluid mapper model could be used to check similar results presented in the previous literature. A value of 71.5 per cent sweepout efficiency was found for the five-spot pattern. This checks closely with published data obtained by both analytical methods and experiments using other types of models. Results obtained for $M = 1$ were used as a reference point for interpretation of the effects of various mobility ratios on the areal sweepout efficiency.

FIVE-SPOT PATTERN

The areal sweepout efficiency was found to vary from a value of 51.8 per cent at $M = 0.093$, to a value of 89.1 per cent at $M = 24.4$. Reproducible results were obtained although some tests were run at a low rate of 0.028 cc/sec and some at a high rate of 0.112 cc/sec. Typical flood patterns at breakthrough of the displacing fluid are depicted by Fig. 2. The interface was found to have accentuated fingering or cusp-

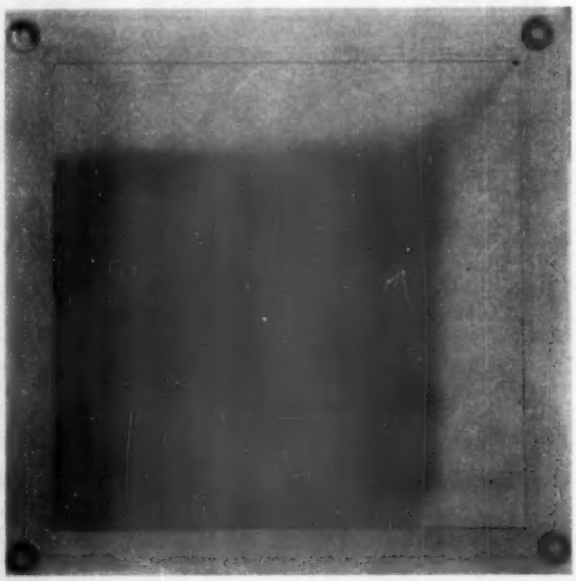


FIG. 2—AREAL SWEEPOUT PATTERN AT BREAKTHROUGH FOR QUADRANT OF FIVE-SPOT PATTERN. M = 1.0.

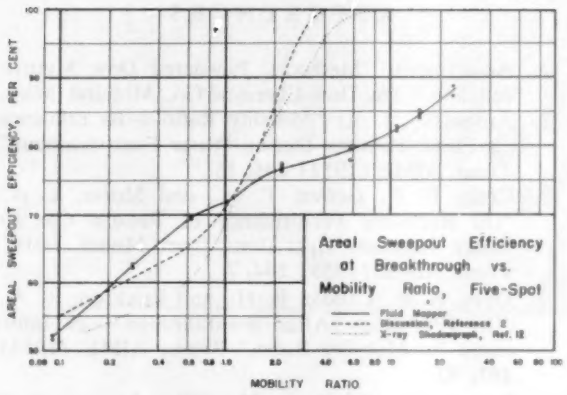

AREAL SWEEPOUT EFFICIENCY, PER CENT
MOBILITY RATIO
Areal Sweepout Efficiency at Breakthrough vs. Mobility Ratio, Five-Spot

FIG. 3

ing for low values of M which became less pronounced with $M \geq 1$. Even with $M > 1$, fingering occasionally occurred in the fluid mapper model at the beginning of a run. Fingering usually disappeared as the front continued to move and expand into the flow area. The disappearance of the fingering was not attributed to diffusion of the dye, but rather to decreasing the width of the small zone of fingering as the interface moved into an area of greater radius.

Results of the five-spot pattern tests are shown in Fig. 3. A comparison of data obtained from the fluid mapper with data obtained from previous investigations, also presented in Fig. 3, shows a wide discrepancy in the sweepout efficiencies for higher values of M, although the data are comparable for lower M values. Previous investigators have reported 100 per cent areal sweepout with values of M between 4 and 8. In the fluid mapper, at $M = 8$ the areal sweepout was only 81.5 per cent and at $M = 24.4$ it was 89.1 per cent. The reason for this discrepancy is not definitely known unless there was some unrecognized model scale effect which entered into the operation of either the fluid mapper or the other models.

Two possible phenomena in the operation of the fluid mapper may explain part of this discrepancy. One is the velocity distribution across the flow space and across the fluid interface. The other is the location of the effective position of the advancing dye front. When the displacing and displaced fluids have the same viscosity, a parabolic velocity distribution will exist across the flow space and the fluid interface.

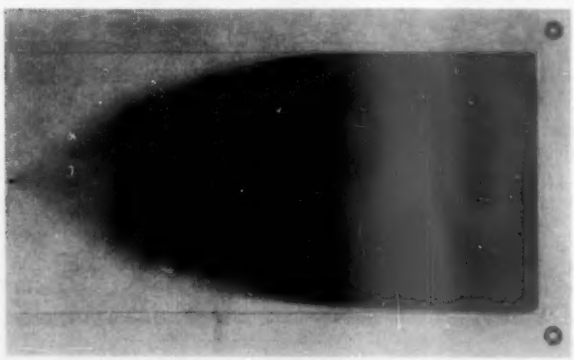


FIG. 4—AREAL SWEEPOUT PATTERN AT BREAKTHROUGH FOR DIRECT LINE-DRIVE PATTERN. M = 1.0.

When the displacing and displaced fluids have different viscosities, it is debatable whether or not the velocity distribution remains parabolic or can be made parabolic by controlling the rate of flow. If the velocity of the interface is not parabolic the behaviour of the fluid mapper would become complex. In the event of vertical interdiffusion at the interface, the operation and theory of the model would become exceedingly complicated.

The location of the advancing dye front is important to the correct interpretation of results. It is difficult to determine the instant when the displacing fluid reaches the producing well. Breakthrough was arbitrarily selected as that point when the "finger" of the displacig fluid reached the producing well. A study of the color intensity in the photographs shows that breakthrough based on this "finger" of dye may have resulted in low areal sweepout efficiencies.

DIRECT LINE-DRIVE PATTERN

The direct line-drive pattern Fig. 4 was studied for the special case in which $b/a = 2$. Results are presented in Fig. 5. These data show the areal sweepout efficiency varies from 58.7 per cent at $M = 0.089$ to 92.0 per cent for $M = 24.8$. In general, the areal sweepout increases for increasing values of M throughout the range of $M = 0.089$ to $M = 24.8$. Muskat[7] has shown that the areal sweepout increases for increasing ratios of b/a. He found that for values of $b/a \geq 1.5$ the areal sweepout efficiency for $M = 1$ is expressed as:

$$E = 1 - 0.441\frac{a}{b}$$

Solution of the equation gives a value of $E = 0.78$ at $M = 1$ for a ratio of $\frac{b}{a} = 2$. However, results in the fluid mapper, for $M = 1$, indicated an areal sweepout of 73 per cent. No apparent explanation is available for the lower value as determined by the model studies, since constant rates of flow were maintained by use of the Zenith pump, and since the flow area was completely enclosed by a barrier during operation of the model.

CONCLUSIONS

Quantitative results obtained in this study apply only to this system and are not necessarily values which

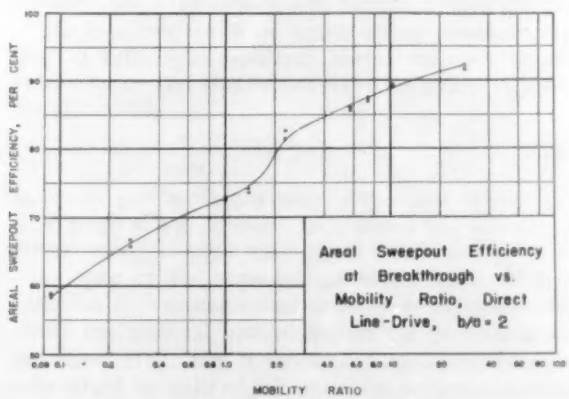

AREAL SWEEPOUT EFFICIENCY, PER CENT
MOBILITY RATIO
Areal Sweepout Efficiency at Breakthrough vs. Mobility Ratio, Direct Line-Drive, b/a = 2

FIG. 5

may be determined from field operations. The fluid mapper models used were operated to simulate a two-dimensional plane in a uniformly homogeneous reservoir. The results obtained with the idealized patterns show that the mobility ratio should be considered in evaluating the economics of a proposed secondary recovery project.

The flexibility and versatility of the fluid mapper model warrants further investigation and application in secondary recovery work as well as in general petroleum engineering. As the model is used and new techniques are developed, it should be possible to determine the velocity distribution and the effective dye front which will permit better interpretation of results. Dimensionally scaled models of the fluid mapper can conceivably be used to determine the fluid front at any time during the primary phase of production in secondary recovery operations. Use of the model with correct mobility ratios would permit a more accurate analysis of the economics of projects to determine the position of the fluid interface at any time for irregular well patterns or to simulate erratic fluid fronts resulting from breakdown of equipment or changes in field operating practices.

ACKNOWLEDGMENTS

Acknowledgment is made to the Stanolind Oil and Gas Co. for sponsoring this study under the Stanolind Oil and Gas Co. Fellowship at the University of Oklahoma. Appreciation is expressed to Professor A. D. Moore, University of Michigan, and to members of the faculty and fellow graduate students in the School of Petroleum Engineering, University of Oklahoma, who offered invaluable assistance and encouragement during this work.

REFERENCES

1. Anonymous: "Methocel, Powdered Dow Methylcellulose," The Dow Chemical Co., Midland, Mich.
2. Aronofsky, J. S.: "Mobility Ratio — Its Influence on Flood Patterns During Water Encroachment," *Trans.* AIME (1952) **195,** 15.
3. Craig, F. F., Geffen, T. M., and Morse, R. A.: "Oil Recovery Performance of Pattern Gas or Water Injection Operations from Model Tests," *Trans.* AIME (1955) **204,** 7.
4. Dyes, A. B., Caudle, B. H., and Erickson, R. A.: "Oil Production After Breakthrough — as Influenced by Mobility Ratio," *Trans.* AIME (1954) **201,** 81.
5. Fay, C. H. and Prats, M.: "The Application of Numerical Methods to Cycling and Flooding Problems," Proceedings, Third World Petroleum Congress, The Hague (1951) sec. II, p. 555.
6. Hele-Shaw, H. S.: "Experiments on the Nature of the Surface Resistance in Pipes and on Ships," *Trans.* Institution of Naval Architects (1897) vol. XXXIX, 145.
7. Moore, A. D.: "Fields from Fluid Flow Mappers," *Jour. Applied Physics,* (1949) **20,** 790.
8. Moore, A. D.: "The Further Development of Fluid Mappers," *Trans.* AIEE (1950) **69,** part II, 1615.
9. Moore, A. D.: "Mapping Technique Applied to Fluid Mapper Problems," *Trans.* AIEE (1952) **71.**
10. Moore, A. D.: "Starting a Fluid Mapper Laboratory," Unpublished notes.
11. Muskat, M.: *Physical Principles of Oil Production,* McGraw-Hill Book Co., Inc., New York, (1949).
12. Slobod, R. L., and Caudle, B. H.: *X-ray Shadowgraph Studies of Areal Sweepout Efficiencies, Trans.* AIME (1952) **195,** 265. ★★★

The CONCEPT "HYDRAULIC RADIUS" in POROUS MEDIA

G. J. HARMSEN

KONINKLIJKE/SHELL-LABORATORIUM
AMSTERDAM

ABSTRACT

It is shown that in any isotropic porous medium there is a fixed ratio, $\frac{\pi}{4}$, between the numerical values of the total pore perimeter per unit of cross-section and the specific surface area per unit of bulk volume. The consequences of this fact on the use of the concept "hydraulic radius" in the case of porous media are examined.

The validity for consolidated sands of Kozeny's relationship and of the formula derived by Carman for capillary rise are discussed.

INTRODUCTION

In the course of time several quantities and relations have been put forward in order to describe the texture of a porous medium and the flow of fluid through it. Among these relations the so-called Kozeny formula and a formula for capillary rise, for both of which Carman[1, 2] has given a derivation, will be specially considered here. These relations are of a semi-empirical nature and the derivations must be considered to have a heuristic significance only. For unconsolidated material they have been satisfactorily confirmed by experiment.

In the derivation of Kozeny's formula[1], which relates permeability to porosity and specific surface area, Carman combines Darcy's law and the generalized Poiseuille's law, valid for cylindrical capillaries of variously shaped cross-section,

$$u = \frac{m^2}{k_o \eta} \cdot \frac{\Delta P}{L}$$

in which u = linear rate of flow, η = viscosity, ΔP = pressure difference along a length L, k_o = a constant, lying between 2.0 and 2.5, for most shapes of cross-section and m = the "hydraulic radius." This hydraulic radius is defined as

$$m = \frac{\text{area of cross-section of capillary}}{\text{perimeter of cross-section of capillary}} \quad . \quad (1a)$$

or as

$$m = \frac{\text{volume of capillary}}{\text{wetted surface of capillary}} \quad . \quad . \quad (1b)$$

Both definitions are equivalent for cylindrical capillaries. This is not the case, however, for porous media. Although the pore volume of a cylinder of homogenous porous material is equal to the pore area in a cross-section multiplied by the length of the cylinder, the product of total pore perimeter of cross-section and the length of the cylinder need not necessarily be equal to the internal surface area.

In deriving Kozeny's relation, Carman chose definition (1b) for m, viz. $\frac{f}{S}$. After introducing an additional factor to account for the tortuosity and interconnection of the pores he arrived at the well-known formula

$$K = \frac{1}{k} \cdot \frac{f^3}{S^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

K being the permeability, k the Kozeny constant, f the porosity, and S the surface area per unit of bulk volume.

The capillary rise h of liquids giving complete wetting[3] in cylindrical capillaries having variously shaped cross-sections can also be calculated by means of a single expression,

$$h = \frac{\gamma}{\rho g m} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which γ = surface tension, ρ = liquid density and g = gravitational constant. In applying this formula to porous media, Carman again chose definition (1b) for m.

In spite of the experimental confirmation of both formulae for unconsolidated sands, one may reasonably doubt the physical justifiability of the preference for definition (1b). For instance, capillary equilibria are determined by radii of curvature, i.e. by cross-sectional dimensions, and not by volume or surface area of the

[1]References given at end of paper.
Original manuscript received in Petroleum Branch office Jan. 6, 1955.

pores. It is therefore desirable to investigate the relation between m according to (1a) and m according to (1b).

DERIVATION

In the following we shall consider a cylinder of porous material of length L, having its axis in the direction $\vec{1}$. Cross-sections are taken perpendicular to $\vec{1}$. The total perimeter of the pores in a cross-section is denoted by p. Further we introduce the concepts "apparent surface area," A_a, defined by

$$A_a = \int_0^L p\, dl \quad \ldots\ldots\ldots\ldots \quad (4)$$

and "true surface area," A_t, the latter being the internal surface area of the cylinder. If the medium is homogeneous, $A_a = pL$.

The difference between the apparent and the true surface area originates from the fact that the Equation 4 does not account for the orientation of the surface. This signifies that at a point 0 of the perimeter an element dA_t of the *true* surface area has been replaced by an element $dA_a = dA_t \mid \cos\theta \mid$ of the *apparent* surface area. Herein θ is the angle between the normal $\vec{n}$ to the pore surface and the normal $\vec{m}$ to the pore perimeter in the plane of cross-section, both in point 0 (see Fig. 1). Consequently A_a can also be defined as

$$A_a = \iint_S \mid \cos\theta \mid dA_t$$

Both definitions are equivalent.

We are concerned with the ratio $q = A_a/A_t$.

EXAMPLE 1

First we shall consider a porous medium consisting of spherical particles of equal radius R. If the cylinder contains N particles, the apparent surface area is N times the apparent surface area A'_a of one particle and the true surface area is N times the true surface area A'_t of one particle. Consequently, according to Equation 4 (see Fig. 2)

$$q = \frac{A'_a}{A'_t} = \frac{1}{4\pi R^2} \int_0^{2R} 2\pi r\, dx =$$

$$= \frac{1}{2R^2} \int_0^{2R} \sqrt{2Rx - x^2}\, dx = \frac{\pi}{4}$$

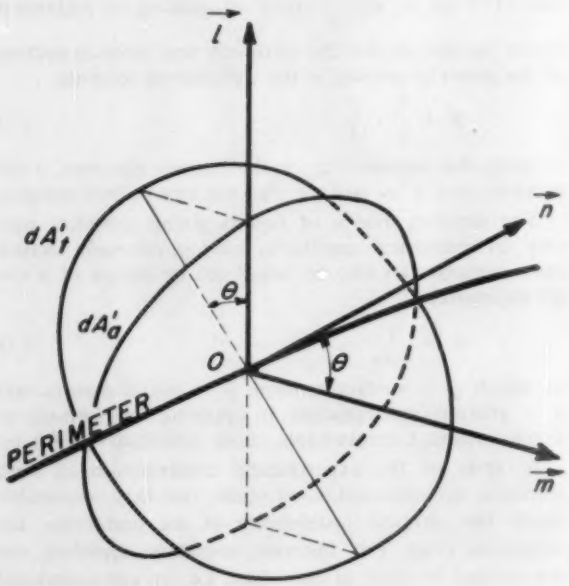


FIG. 1

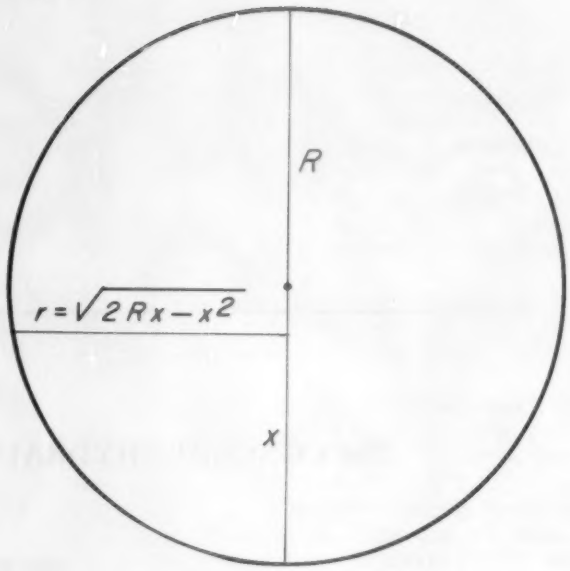


FIG. 2

EXAMPLE 2

Next we shall deal with a medium composed of equal particles of arbitrary shape, which is assumed to be isotropic, so that the particles are orientated at random. The apparent surface area of the porous mass in this case is N times the *mean* apparent surface area of one particle, which is the average over all prevailing orientations of the particles. If the dimensions of the cylinder under consideration are large compared with the dimensions of the particles, this mean area is closely approximated by an integration over all directions in space.

Let us consider an element dA'_t of the surface of a given particle. Its contribution to the apparent surface area being $dA'_a = dA'_t \mid \cos\theta \mid$, its contribution to the *mean* apparent surface area of the particle is obtained by averaging dA'_a over all directions of its normal $\vec{n}$ (see Fig. 3), or

$$\overline{dA'_a} = \frac{1}{4\pi} \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_0^{2\pi} dA'_a \cos\theta\, d\phi\, d\theta =$$

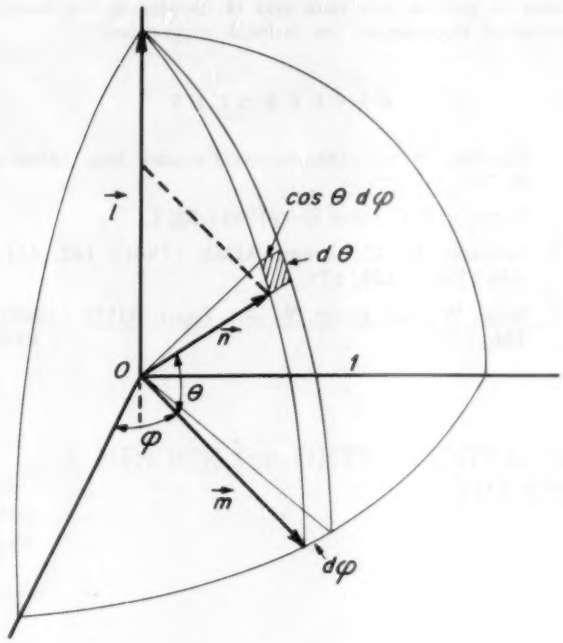


FIG. 3

$$\frac{dA'_t}{4\pi} \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_{0}^{2\pi} \cos^2\theta \, d\phi \, d\theta = \frac{\pi}{4} dA'_t .$$

Thus the entire mean apparent surface area of one particle is

$$\overline{A'_a} = \frac{\pi}{4} A'_t$$

so that q, for an isotropic medium consisting of equal particles of any shape, is $\frac{\pi}{4}$.

EXAMPLE 3

The foregoing considerations can be extended to any isotropic porous medium, both unconsolidated and consolidated. To that end we assume the internal surface of the porous cylinder to be built up of surface elements of equal area dA_t. In an isotropic medium these surface elements are orientated at random, so that their mean contribution to the apparent surface area is

$$\overline{dA_a} = \frac{1}{4\pi} \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \int_{0}^{2\pi} dA_a \cos\theta \, d\phi \, d\theta = \frac{\pi}{4} dA_t$$

Consequently

$$A_a = \frac{\pi}{4} A_t \text{ or } q = \frac{\pi}{4}$$

Quite generally, therefore, for every isotropic porous medium, the apparent surface area is $\frac{\pi}{4}$ times the true surface area of the medium, or in other words the pore perimeter of the unit of cross-section is numerically equal to $\frac{\pi}{4}$ times the specific surface area of the unit of bulk volume. Consequently the ratio of m by definition (1b) to m by definition (1a) is also equal to $\frac{\pi}{4}$.

DISCUSSION

The results obtained show that the ratio q of internal surface area to perimeter of cross-section does not reflect any structural property of a porous medium except anisotropy. The constant ratio at the same time abolishes the ambiguity in applying the concept of hydraulic radius to porous media, because the substitution of $\frac{f}{S}$ for m is always permissible, provided that a proportionality factor is added to account for the difference in m according to both definitions. In most cases it will be difficult to choose between the two definitions (1), so that m in fact will only serve to introduce f and S in the formulae in the ratio $\frac{f}{S}$. Experiments are necessary to verify the resulting proportionality and to determine the magnitude of the proportionality factor. Actually this has been done in deriving Kozeny's relation (2). For this reason also the application of Equation 3 derived on the basis of capillary rise in cylindrical capillaries to porous media, should include the introduction of a proportionality constant k', so as to give

$$h = k' \cdot \frac{\gamma}{\rho g} \cdot \frac{S}{f} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3a)$$

especially as the capillary rise will be determined by the ratio of pore perimeter to pore area, so that $m = \frac{4}{\pi} \cdot \frac{f}{S}$ has to be substituted. It would appear to be fortuitous that k' is found to have a value of about 1 for unconsolidated sands. It is not permissible, however, to omit k' when applying the formula to consolidated media, for the same reason as that giving rise to a difference in Kozeny's constant k with respect to its value for unconsolidated sands.

Leverett[3] has proposed representing the dependence of the capillary pressure, P_c, of a medium on its wetting fluid saturation, s_w, in a dimensionless form, by plotting the quantity $j\ (s_w) = (P_c/\gamma)\ (K/f)^{1/2}$ instead of P_c itself against s_w, and has shown experimentally that the capillary pressure curves then coincide for unconsolidated sands. This fact to some extent illustrates the structural conformity of these sands and makes the constant value of k and k' found in these cases plausible. In the same way, however, the differences between the $j\ (s_w)$-curves obtained on consolidated material, e.g. by Rose and Bruce,[4] show their unconformity in texture and give strong support to the view that both k and k' will depend on the type of formation.

Extrapolation of $j\ (s_w)$ to $s_w = 100$ per cent, as done by Rose and Bruce, gives the dimensionless thresh-

old pressure $(P_x/\gamma)\ (K/f)^{1/2}$. Substitution of $P_x = \rho gh$ and combination with Equations 2 and 3a gives

$$\lim_{s_w \to 1} j\,(s_w) = k'/k^{1/2}$$

and not $1/\sqrt{k}$ as stated by Rose and Bruce. Additional information on the applicability of Equations 2 and 3a for consolidated media will consequently be required in order to allow the constants k and k' to be evaluated.

ACKNOWLEDGMENT

The author wishes to thank the management of the Koninklijke/Shell-Laboratorium, Amsterdam for permission to publish this note and H. Bolder of the mathematical department for helpful suggestions.

REFERENCES

1. Carman, P. C.: Discussions Faraday Soc. (1948) **3,** 72.
2. Carman, P. C.: *Soil Sci.* (1941) **52,** 1.
3. Leverett, M. C.: *Trans.* AIME (1941) **142,** 151; ibid (1942) **146,** 175.
4. Rose, W., and Bruce, W. A.: *Trans.* AIME (1949) **186,** 127.

★★★

TECHNICAL NOTE 314

A DEVICE for DETERMINING the CONCENTRATION of FORMATION TREATING ACIDS

J. L. HUITT

MAGNOLIA PETROLEUM CO.
DALLAS, TEX.

Some of the problems associated with the acid treatment of oil wells are related to the control of the composition of formation treating acid. One test usually made at the well site is the determination of the acid concentration. Heretofore, the concentration of the acid delivered to the well site usually has been interpreted from a hydrometer measurement of the specific gravity of the acid solution. Experience has shown that this indirect measurement of acid concentration can give erroneous results. More reliable results are, of course, obtainable by the titration method; however, this method is not easily adapted to well-site testing.

To overcome these objections, a device was developed for use in the field which permits determination of the concentration of treating acid both quickly and accurately at the time of the acid treatment. Its purpose was three-fold, namely, to determine: (1) the concentration of the fresh treating acid, (2) the concentration of the spent acid returning from the well, and (3) the solubility of formation samples in treating acid.

The device was designed to operate on the principle of the stoichiometric relation between the calcium carbonate—hydrochloric acid reaction and the carbon dioxide gas resulting from the reaction. By confining the carbon dioxide gas within a reaction cell of the type shown in Fig. 1, the pressure inside the cell is increased. Since the pressure is an indication of the quantity of carbon dioxide gas produced, it may be used to estimate the concentration of the acid, provided an excess of calcium carbonate is used. From information on the volume of the reaction cell, the volume of acid used, and the pressure and temperature of the gas after the completion of the reaction, the concentration of the treating acid may be computed.

Manuscript received in Petroleum Branch office on Aug. 10, 1955.

The reaction cell is essentially a pressure vessel equipped with a pressure gage, temperature indicator, pressure release valve, and a special sample holder. Plastic and metal construction makes the cell both rugged and acid-resistant. The sample holder is so designed that a sample of calcium carbonate (or sample of carbonate rock) can be dropped into the acid solution after the cell is closed. The manner in which the folded paper containing the carbonate sample is held by the sample holder is shown in Fig. 2.

Other features of a typical reaction cell and materials used in an acid concentration test are as follows:

The total volume of the cell is approximately 482 ml, of which 462 ml may be considered as gas space for computation purposes. For the concentration test, 10.0 ml of treating acid and 10.0 ml of water are placed in the cell. The water is used to rinse any remaining acid from the container used to measure the acid-sample volume, and to increase the acid volume in the cell so that the calcium carbonate sample is covered with liquid. A calcium carbonate sample of approximately 2½ gm is used. This size carbonate sample is

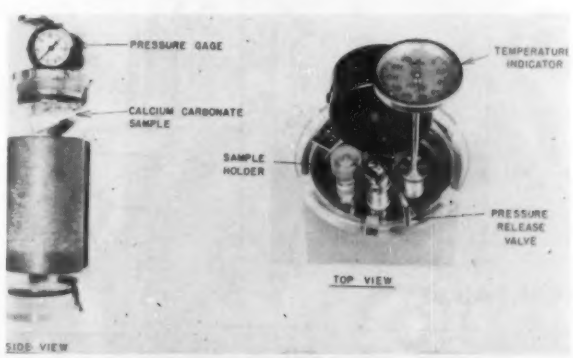


FIG. 1 — REACTION CELL.

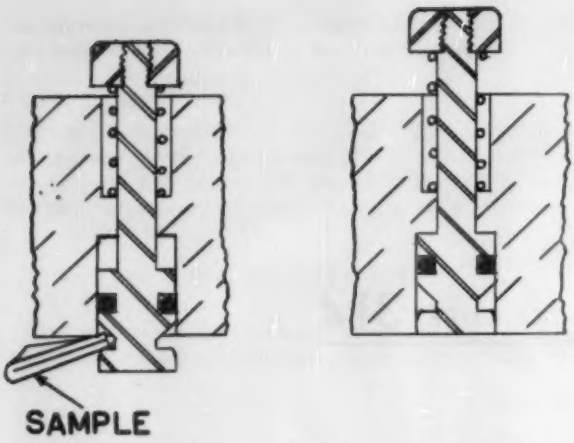


FIG. 2 — CROSS SECTION OF SAMPLE HOLDER.

sufficient for acid concentrations usually encountered in oil well acidizing. A similar procedure is followed where it is desired to determine the concentration of spent acid returning from the well. Actually the cell design is such that, if the specified volume (10 ml) of hydrochloric acid is used, the actual pressure (psig) build-up during a test is very nearly equivalent, numerically, to the concentration of the acid, expressed as weight per cent.

The reaction cell may also be used for the determination of the solubility of carbonate rock samples in treating acid. The same stoichiometric and PVT relations used in the acid concentration test are utilized to estimate the weight per cent of the rock soluble in an excess of acid. In this test, a 2¼ gm rock sample and 20 ml of treating acid are preferably used.

The results of the use of the reaction cell in the field testing of treating acids have been excellent. The results thus far have shown that the acid concentration determined on samples at the well sites with the cell are within 0.5 weight per cent of the acid concentration determined in the laboratory on the same samples by titration methods. Through use of such a reaction cell, improved control over concentrations of acids is permitted which, in turn, should lead to improved results obtained through use of formation treating acids. ★★★

TECHNICAL NOTE 304

A RESULT OF SP LOG INTERPRETATION

PAULO VARJÃO DE ANDRADE
JUNIOR MEMBER AIME

CONSELHO NACIONAL DO PETRÓLEO
SALVADOR, BAHIA, BRAZIL

INTRODUCTION

Since 1949, attention has been directed in this laboratory to the interpretation of SP logs. It has been the aim of the work to get connate water resistivities to use in quantitative interpretation of the resistivity curves. Wyllie's theory[1] was taken as the fundamental working hypothesis as it would provide a correct theoretical background to support the results. In order to have an idea of the precision of the method, it was decided to make a series of interpretations in wells which produced only water and to compare the calculated results with resistivities obtained from chemical analysis of water samples.

Several water analyses and electrical logs were available from wells in the Sergi′ sands in several fields of the Bahian Reconcavo. The Sergi′ sands are the highest member of the Brotas formation, presumably of Lower Cretaceous age, and were deposited all over the basin. They constitute a homogeneous body and can be correlated over distances of tens of miles with only minor changes in lithology. The upper part of the Sergi′ known as "C zone," is a medium to fine grained sandstone, medium consolidated to friable, with finely disseminated clay, 15 to 30 ft thick, good porosity and permeability. Fig. 1 shows a log of part of the upper Sergi′ with the shale section overlying it.

Water samples came from formation tests, being collected in the lower part of the column. In case of mud contamination, they were discarded. Analysis comprised routine determinations of chloride, sulfate, bicarbonate and carbonate, calcium and magnesium. Sodium was calculated by difference. Resistivities of water and mud were obtained using either the Schlumberger salinity-resistivity chart[2] or a combination of the said chart with Dunlap's method[3] (the low sulfate content of the brines made this method very simple and accurate). Bottom-hole temperatures were available either from log headings or from direct measurements made with a maximum thermometer. In order to avoid the influence of resistivity on the amplitude of the *SP* "peak," only water wells were used in this study. Corrections for bed thickness were unnecessary in the wells studied.[4] All wells were rotary drilled.

Calculations were made as follows: the SP was measured from an appropriate shale line and taken to Wyllie's chart (an enlargement was actually used). The ratio R_m/R_w was read from the right temperature curve and R_w calculated from the known R_m. Table 1 shows the results obtained, reproduced graphically in Fig. 2.

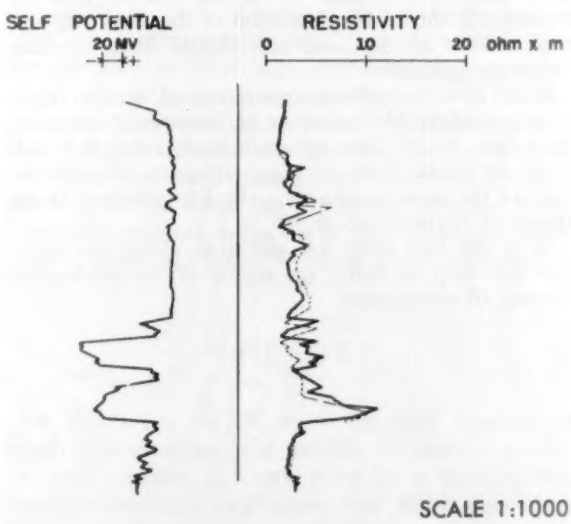


FIG. 1 — LOG OF PART OF THE UPPER SERGI WITH THE SHALE SECTION OVERLYING IT.

Original manuscript received in Petroleum Branch office on Nov. 29, 1954. Revised manuscript received Aug. 29, 1955.
[1]References given at end of paper.

TABLE 1 — CALCULATED AND MEASURED VALUES OF WATER RESISTIVITIES

Well	Top Sergi subsea, ft.	S.P. deflection mV.	Mud resistivity ohm x m.	Calc. resistivity ohm x m.	Meas. resistivity ohm x m.	Water resistivity ohm x m., at 77°F.
Ag-1	3935	93	.88	.057	.035	.06
C-82	6547	105	.74	.040	.026	.06
Dj-10	616	63	8.2	1.15	.18	0.24
Dj-ia-2	1006	85	8.0	.55	.13	0.17
Mj-1	3563	95	.90	.056	.033	.06
Pv-2	3331	100	.75	.041	.028	.055
Pv-3	3341	75	.69	.076	.042	.074
Vc-1	2569	53	.57	.116	.048	.076

Note: Resistivities given at bottom-hole temperature except in the last column.

INTERPRETATION

An inspection of Fig. 2 shows that the resistivities from the logs are too high. As the results followed a general trend, it was considered advisable to calculate the relationship between actual and apparent values of connate water resistivities and to investigate the cause of discrepancy.

The equation of the line in Fig. 2 is

$$\log R_w = 0.582 \log R'_w - 0.748 \quad . \quad . \quad (1)$$

Taking this value into Wyllie's equation, written as

$$SP = K \log (R_m/R'_w) \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and making the necessary algebraic operations, the following equivalent formulas are obtained:

$$SP = 1.718\, K \log (R_m/R_w) - K\,(0.718 \log R_m + 1.285) \quad . \quad . \quad (3)$$

and

$$SP = K \log (R_m/R_w) + 0.718\, K \log (0.0162/R_w) \quad . \quad . \quad . \quad . \quad (4)$$

Equation 3 is very useful for calculation of Sergi' connate water resistivity.

Equation 4 can be written in general as

$$SP = K \log (R_m/R_w) + A\, K \log (R_s/R_w) \quad (5)$$

The form of Equation 5 suggests that Wyllie's electromotive force $K \log (R_m/R_w)$ is not the only force involved in *SP* measurement, there being another emf resulting from the difference in concentration of the connate water and the solution adsorbed at the clay surface. Going still further, it is seen that in the present case $R_s = 0.016$ is the resistivity of a saturated solution of NaCl in the range of temperatures commonly encountered in oil-sands. Hence, for the Sergi' sandstone at least, the adsorbed layer around the clay particles must be a saturated solution of chloride ions. The constant coefficient A in the second term of Equation 5 should be a function of the clay type and clay content of the sand and should be a constant for every geological formation.

It is seen that the interpretation of data at hand led to confirm McCardell et al hypothesis[5] regarding the origin of *SP*. The approach made hereinbefore is easier to follow from a "practical" point of view but has not the same precise theoretical foundations as the theory of Humble's group.

It is felt that more investigations along this direction will help to clarify the nature of the phenomena causing *SP* appearance.

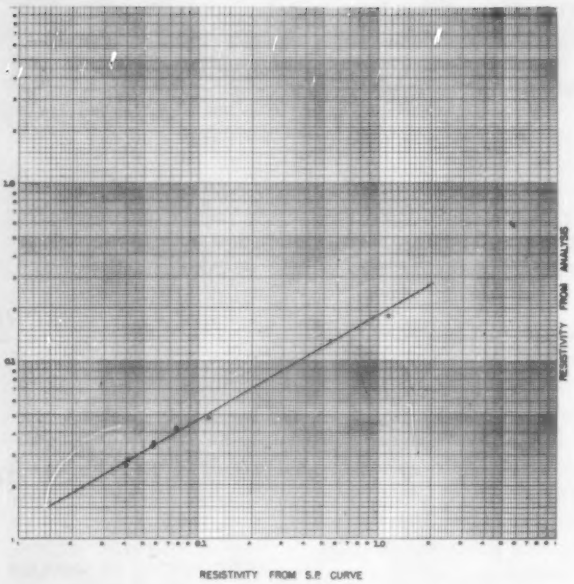


FIG. 2 — CALCULATED AND MEASURED VALUES OF WATER RESISTIVITIES.

ACKNOWLEDGMENTS

Thanks are due to the president of the Conselho Nacional do Petroleo, Brazil, for permission to publish this Note. The work was conducted under the general supervision of Pedro de Moura, chief engineer for the Bahia, Brazil, area. J. Trassard (Schlumberger Surenco Co.), H. Hugel, and J. Araujo discussed the subject.

NOMENCLATURE

R_w = True resistivity of connate water.
R'_w = Apparent resistivity of connate water.
SP = Self potential.
K = A function of temperature.
A = A function of the clay type and content.
R_s = Resistivity of a saturated solution of NaCl.
All resistivities given at bottom-hole temperature.

REFERENCES

1. Wyllie, M. R. J.: *Trans.* AIME (1949) **186,** 17.
2. Schlumberger Document number 3, pg. 7, 1949.
3. Dunlap, H. F., and Hawthorne, R. R.: *Trans.* AIME (1951) **192,** 373.
4. Doll, H. G.: "The SP log: Theoretical Analysis and Principles of Interpretation," *Trans.* AIME (1948) **179,** 146.
5. McCardell, W. M., Winsauer, W. O., and Williams, M.: *Trans.* AIME (1953) **198,** 41. ★★★

AIME

PETROLEUM TRANSACTIONS

STUDIES on PRESSURE DISTRIBUTION in BOUNDED RESERVOIRS at STEADY STATE

C. S. MATTHEWS
MEMBER AIME
H. C. LEFKOVITS

SHELL DEVELOPMENT CO.
HOUSTON, TEX.

T. P. 4164

ABSTRACT

The purposes of this study are (a) to determine the accuracy of a previously proposed method for calculating average reservoir pressure and (b) to find a method for estimating the shape of the drainage area of each well in a bounded reservoir. Both numerical and experimental methods are used to determine the pressure distribution and the location of drainage boundaries in idealized reservoirs at steady state. A number of photographs are included which show flowlines and drainage areas in reservoir models of various shapes. Results from these studies are then compared with those from the previously proposed method for calculating average reservoir pressure.[1] It is concluded that the previously proposed method is sufficiently accurate for most reservoir engineering purposes. In addition, some simple methods are given for estimation of shapes of drainage boundaries.

INTRODUCTION

A method for the determination of the average pressure in a bounded reservoir was previously developed by Matthews, Brons, and Hazebroek,[1] and presented at the Petroleum Branch Fall Meeting in 1953.† In applying this method, the reservoir was first divided into drainage volumes; second, the average pressure in each drainage volume was calculated; and third, these drainage volume pressures were averaged volumetrically to give the average pressure in the reservoir. It was shown that each well's individual drainage volume, at steady state, is proportional to the well's production rate; however, the question of how to estimate accurately the shape of these drainage volumes could not be answered. Furthermore, in calculating the average pressure for each drainage area, the actual drainage areas, which are in general quite asymmetric in shape, are replaced with one of the symmetric prototypes given in T.P. 3876. A question may then be raised as to how accurately the symmetrical figures depict the pressure behavior of the actual unsymmetrical drainage areas. The study reported on in the present paper was made in an attempt to shed light on the above questions.

METHODS

It was shown in T.P. 3876 that after a period of steady rate of withdrawal the rate of pressure decline becomes constant at every point in a bounded reservoir containing a single-phase fluid whose compressibility is small and constant and whose viscosity is con-

Publication No. 60, Shell Development Co., Exploration and Production Research Division, Houston, Tex.

Original manuscript received in Petroleum Branch office on July 22, 1955. Revised manuscript received Oct. 17, 1955.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1955, should be in the form of a new paper.

[1]References given at end of paper.
†This paper will hereafter be referred to as T.P. 3876.

stant. The differential equation at steady state for the pressure p at every point (x, y) of the drainage volume v_i is

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = -\frac{q_i \mu}{k v_i} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the pressure distribution throughout the drainage volume is known at any one instant at steady state, it can be obtained at any other instant merely by subtracting a constant amount from the pressure at each point, the magnitude of this amount being the difference of the average pressures at those instants. This follows from the fact that $\partial p/\partial t$ is constant so that the pressure at all points, as well as the average pressure, decreases at the same rate, and hence by the same amount over any period of time. The decrease in average pressure in the drainage volume v_i from a time t_1 to the time t_2 is $q_i(t_2 - t_1)/(cfv_i)$.

Both numerical and experimental methods have been used to obtain solutions of Equation 1. The numerical method used was Southwell's "relaxation method."[2] Equation 1 was replaced by the finite difference equation

$$p_o = \frac{p_1 + p_2 + p_3 + p_4}{4} + \left[\frac{q\mu}{kv}\right]\frac{a^2}{4}, \quad . \quad (2)$$

where p_1, p_2, p_3, and p_4 denote the pressures at the immediately neighboring grid points of the point with pressure p_o in a square net of mesh side a. The boundary condition that there be no flow across the boundary of the region was satisfied by making the gradient at the boundary zero. The boundary condition at the well was satisfied by assuming that the pressure varied logarithmically with distance from the well in a small region around the well.

A faster method of obtaining the pressure and flowline distribution was devised in Shell's E & P Research Laboratory, following the work of Moore.[2] The method used a flow model to simulate the flow of the fluid in the reservoir.

Considering the reservoir at steady state, we see that a model must reflect the fact that no flow occurs over the outer boundaries, and further, that at the steady state each unit volume in the reservoir is dropping in pressure at the same rate and thus contributing to the total efflux at an equal rate. A flow model which does reflect this situation is shown schematically in Fig. 1.

The model consists of sand held between two horizontal screens to simulate the reservoir and of tubing in the sand to simulate the "well-circle."† Water enters the tank in which the model is placed, flows up through the sand and over the top of the screen to the well. It then flows down the wells and out to the sink. Relative flow rates were obtained from times required to fill calibrated bottles in the sink. Preliminary rate adjustments were made with rotameters (not shown in Fig. 1). A constant level was maintained in the water outside the model by a simple drain.

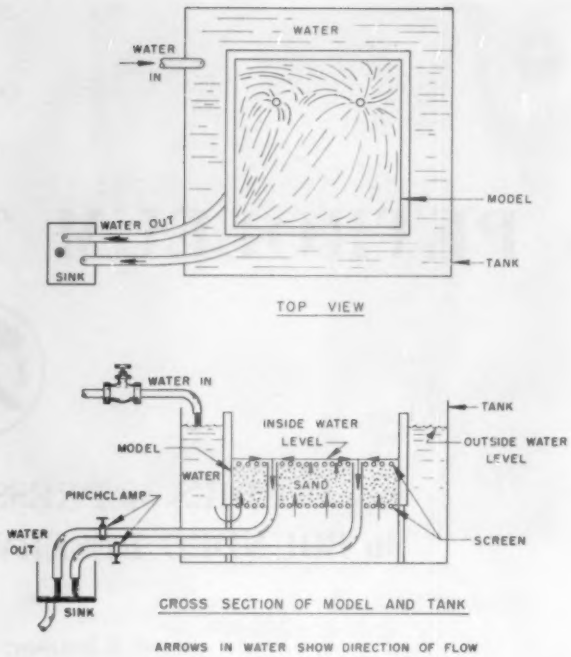


FIG. 1 — FLOW MODEL.

When crystals of potassium permanganate are sprinkled over the top screen, the flowlines of the water are depicted as the water flows over the screen to the well.

The sand is chosen fine enough that at a suitable rate the drop in flow potential of the water as it flows to the wells over the upper screen is small compared with the drop in flowing through the sand bed. As a consequence of this, the water leaves the screen (upward) at a substantially uniform rate at every point. It is easy to show that the pressure distribution in the layer of water above the upper screen satisfies the same differential equation as does the pressure in a compressible fluid at steady state in a bounded reservoir. Considering the meaning of this in terms of reservoir behavior, it can be seen that the uniform water entry is analogous to a uniform expansion of each unit volume of fluid in a bounded reservoir. As each unit volume expands uniformly it furnishes fluid at an equal rate to the total efflux. In other words, this is the steady-state situation as discussed more fully in T.P. 3876. That it rather accurately depicts the steady-state flowlines is shown by the good agreement achieved when a problem to be discussed later was solved both numerically and by this system.

DETERMINATION OF PRESSURE DISTRIBUTION AND DRAINAGE AREA

NUMERICAL

The relaxation solution of Equation 2 yields the pressure at the grid points of the net chosen. Equipressure

†To preserve true geometrical similarity between this model and a reservoir, the "wells" would need to be very small in the model. However, since the flow in the reservoir will probably be radial for some distance near the well anyway, small error is introduced by making the "wells" large. It is necessary to make the "wells" large to avoid "coning" and inertial effects which would arise near a smaller well at rates suitable for model studies. We may call the tubing cross section the "well-circle" to emphasize the fact that it is not a model of the wellbore but of a somewhat larger circle around the wellbore.

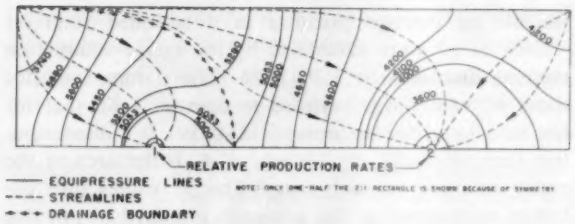


FIG. 2A — PRESSURE DISTRIBUTION OBTAINED BY RELAXATION, RELATIVE PRODUCTION RATES 1 AND 2 IN A 2:1 RECTANGLE.

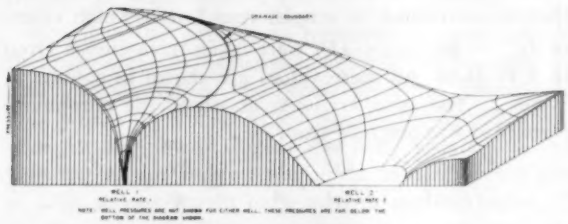


FIG. 2B—PRESSURE DISTRIBUTION IN A 2:1 RECTANGLE.

lines are then obtained by interpolation between grid points, and the flowlines are sketched in, orthogonal to the equipressure lines. Fig. 2A shows a typical result. After the flowlines are sketched in, it will be found that there is one flowline about which the lines on either side diverge—those on one side go to one well and those on the other side to another well. This particular flowline, then, is a drainage boundary. In every sense this boundary at steady state might well be replaced by a true impermeable boundary between the wells without influencing the problem. The oblique projection in Fig. 2B, where the pressures are plotted vertically, shows the drainage boundary more clearly. The areal average pressure inside each drainage area was put on a dimensionless basis by dividing by $q\mu/4\pi kh$ where q was the production rate for that area.

EXPERIMENTAL

Photographs of the flow model show a series of flowlines traced out by the fluid as it flows over the screen to the well. The pressure distribution in the model may be obtained by analyzing these photographs.

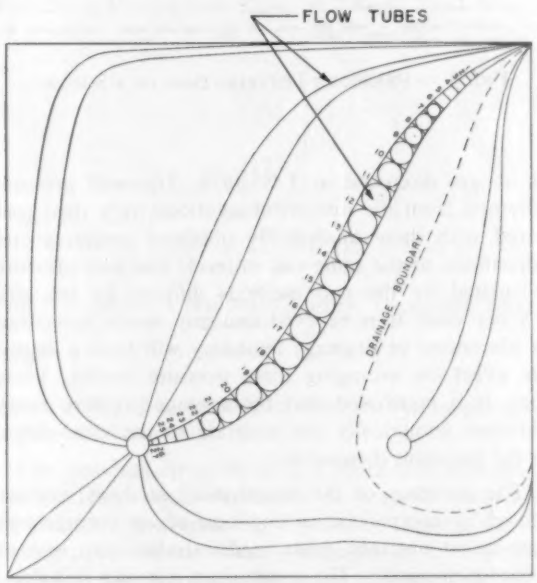
The analysis is begun by tracing off the flow pattern and by using the pattern to form flow tubes as shown in Fig. 3. The rate of flow in the tube varies from point to point. The flow rate is zero at the outer boundary and as the cumulative area of the tube increases in coming to the well, the flow rate increases proportionately. This follows from the fact that flow enters the top layer of water above the screen at an equal rate everywhere. Therefore, we may find the rate of flow past any line such as 5 in Fig. 3 by finding the area enclosed by the tube between the boundary and line 5. We next break the stream tube into curvilinear squares of equal resistance to flow, using the circling-in technique of Moore.[2]

From the curvilinear squares and from the measurements of area which give the rates of flow at various points in the tube, we may calculate the pressure drop as shown in the appendix. A typical result showing a few of the equipressure lines obtained by analysis of Fig. 3 is shown in Fig. 4. Photographs of two of the flow patterns are shown in Fig. 5. The numbers in the margins near the wells indicate relative flow rates.

RESULTS

ACCURACY OF RESULTS

To obtain an idea of the accuracy of the numerical solutions, the pressures at the flowing wells were calculated analytically for the case of the 2:1 rectangle with symmetrically spaced wells flowing in a 2:1 ratio. This analytic calculation was made by using the method



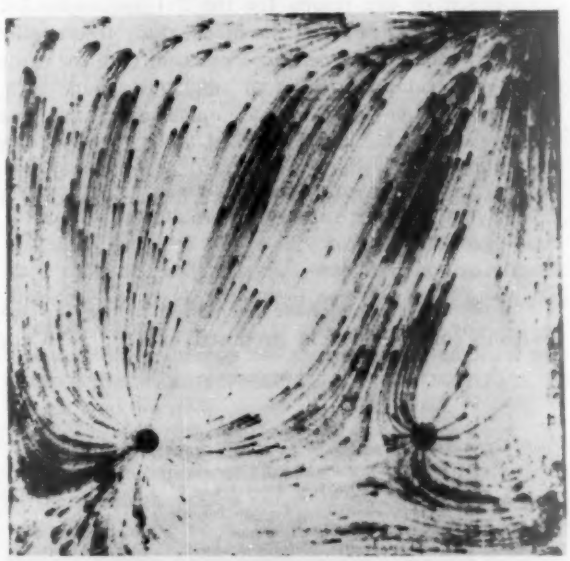
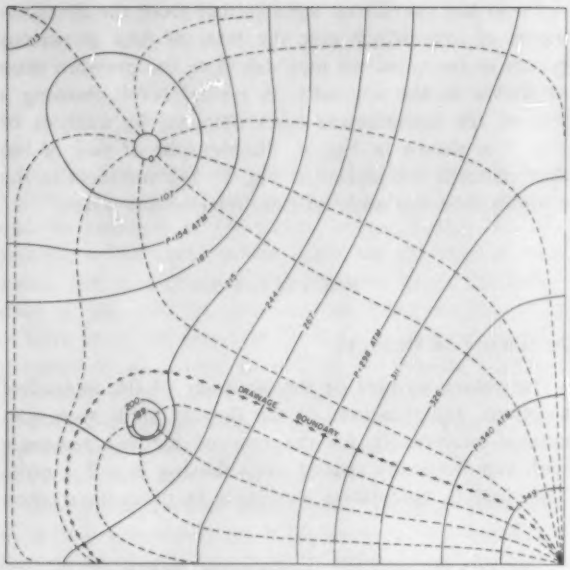


FIG. 3 — ANALYSIS OF FLOW-MODEL PHOTOGRAPH.



NOTE: PRESSURES ARE FOR THE RATES $\frac{q\mu}{4\pi kh} = 43.60$ AND $\frac{q\mu}{4\pi kh} = 10.84$ ATM WHERE 4 IS THE UPPER WELL AND 1 THE LOWER

FIG. 4 — PRESSURE DISTRIBUTION IN A SQUARE.

of images discussed in T.P. 3876. The well pressures obtained from the numerical solutions were then compared with these analytically obtained pressures after adjustment to the same datum level. The well pressures calculated by the two methods differed by less than 0.5 per cent. It is believed that any minor inaccuracy in placement of drainage boundary will have a negligible effect on averaging these pressure results. Therefore, it is concluded that the average pressure results obtained numerically are accurate to the same degree as the pressures themselves.

The accuracy of the model-study analyses was estimated by comparison in one case of an average pressure result obtained from model studies with that obtained numerically. The comparison is shown in Table 1. Comparison of the results for the 2:1 rectangle, 2:1 flowing ratio, indicate that the model-study results may be in error by 0.3 per cent to 1 per cent with the error being greater in the region of smaller drainage area. However this comparison was made using the first model-study results, and the model-study technique has been improved considerably since that time; therefore it is believed that these indicated errors are maximum ones.

DISCUSSION OF RESULTS

The results obtained have been used to test the applicability of the method proposed in T.P. 3876 for calculating average pressure in a bounded reservoir. Values of p^* were calculated by the image summation method discussed in T.P. 3876. The datum level for these p^* values was adjusted to coincide with that for the model and for the numerical studies at a dimensionless time, $kt/f\mu cA_t = 10$, where A_t is the area of the entire reservoir in each case.† The p^* values thus obtained correspond to the pressures obtained in practice by extrapolating to infinite shut-in time the plot of pressure versus log $[\triangle t/(t + \triangle t)]$. From these values of p^* and average pressure results, the quantities

$$(p^* - \bar{p})/(q\mu/4\pi kh)$$

were calculated as given in column 6, Table 2.

The complex drainage boundaries in each case were then approximated by simpler ones,‡ after which values of $(p^* - \bar{p})/(q\mu/4\pi kh)$ were taken from curves given in T.P. 3876. All these values are shown in column 7, Table 2. The time $kt/f\mu cA_t$ at which the corrections were read was obtained from

$$\frac{kt}{f\mu cA_t} = \frac{kt}{f\mu cA_t} \cdot \frac{A_t}{A_t} = 10\,\frac{\Sigma q_i}{q_i}.$$

The term A_i is the drainage area of the ith well. As

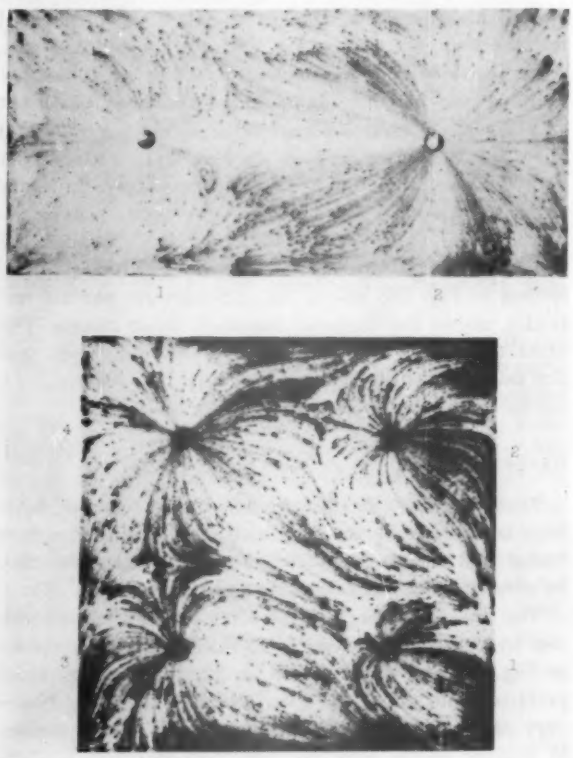


FIG. 5 — FLOWLINES OBTAINED IN MODEL STUDIES.

TABLE 1 — ACCURACY OF MODEL-STUDY RESULTS
Two Wells in a 2:1 Rectangle
Relative Flow Rates 1 and 2

Flow Rate	Dimensionless Average Pressure From Numerical Studies	From Model Studies	Difference	% Difference
1	21.22 ± 0.10	21.43	0.21	1
2	8.73 ± 0.05	8.70	0.03	0.3

†Any value of the dimensionless time large enough to place all results in the steady-state period could have been used in setting the datum level.

‡Details of the approximation method are discussed in the next section.

mentioned above, $kt/f\mu cA_r$ was taken to be 10 to place all results in the steady-state period.

Results are shown in Table 2. It is evident from Table 2 that in every case the method of T.P. 3876 was able to give a good approximation to the true correction $(p^* - \bar{p})/(q\mu/4\pi kh)$ for each drainage area. For example if we take $q\mu/4\pi kh = 20$ psi, then the errors in pressure made by using the simplified method of T.P. 3876 are less than 20 psi and usually less than 10 psi. If the corrections $(p^* - \bar{p})$ are neglected, errors over 100 psi will arise. Thus the corrections of T.P. 3876 greatly improve the accuracy of the results.

Selection of Prototype Curves

It was found possible to represent all asymmetrical drainage areas by rectangles, squares, or triangles, or combinations thereof. To decide upon the symmetrical area which most closely represented the asymmetrical area, the asymmetrical area was first "squared-up." In squaring-up, an attempt was made to balance the loss of area in one region by a gain in another region of similar pressure. The true drainage areas and the squared-up areas are shown in Fig. 6.

Next the square or rectangular drainage area most like the squared-up area was selected from among the prototypes available in T.P. 3876. The corrections $(p^* - \bar{p})/(q\mu/4\pi kh)$ were then read at the proper times. In some cases where the squared-up drainage area looked to be intermediate to two of the prototypes available, averages of the $(p^* - \bar{p})/(q\mu/4\pi kh)$ values for these two prototypes were used. The prototypes shown in Fig. 6 were used to calculate the results given in Table 2.

TABLE 2 — APPLICABILITY OF THE METHOD OF T.P. 3876 FOR CALCULATING AVERAGE RESERVOIR PRESSURE.

Example	Reservoir	Relative Rate of Well	Observed p^* $q_D/\sigma kh$	Observed $\bar{p}$ $q_D/\sigma kh$	Observed $p^* - \bar{p}$ $q_D/\sigma kh$	T.P. 3876[a] $p^* - \bar{p}$ $q_D/4\pi kh$	Error	Error in psi[b]
A	1 / 2	1	27.79	21.22	6.57	6.38	−.19	−4
		2	14.49	8.73	5.76	5.20	−.56	−11
B	1' / 1	1	14.70	8.83	5.87	5.97	+.10	+2
		1'	15.96	12.14	3.82	4.20	+.38	+8
C	1 / 3 / 8	1	95.52	93.90	1.62	2.50	+.88	+18
		3	29.15	27.98	1.17	1.72	+.55	+11
		8	12.90	7.65	5.25	5.25	0	0
D	1 / 3.94	1	37.38	32.25	5.13	5.10	−.03	−1
		3.94	10.40	5.32	5.08	5.00	−.08	−2
E	4.10 / 1	1	29.25	25.99	3.26	3.23	−.03	−1
		4.10	9.49	5.31	4.18	4.02	−.16	−3
F	4.16 / 1 / 1.98	1	31.11	24.59	6.52	6.74	+.22	+4
		1.98	19.81	13.54	6.27	6.09	−.18	−4
		4.16	10.43	5.01	5.42	4.87	−.55	−11
G	3.98 / 2.01 / 2.82 / 1	1	40.30	34.51	5.79	6.09	+.30	+6
		2.01	20.90	14.38	6.52	6.85	+.33	+7
		2.82	15.44	9.42	6.02	5.85	−.17	−3
		3.98	11.53	5.23	6.30	6.17	−.13	−3

[a] Models used for the drainage areas are shown in Figure 10. The brace, {, about two models means that an average of the values for these two models was used.

[b] The error in psi is calculated on the assumption that $q\mu/4\pi kh = 20$ psi.

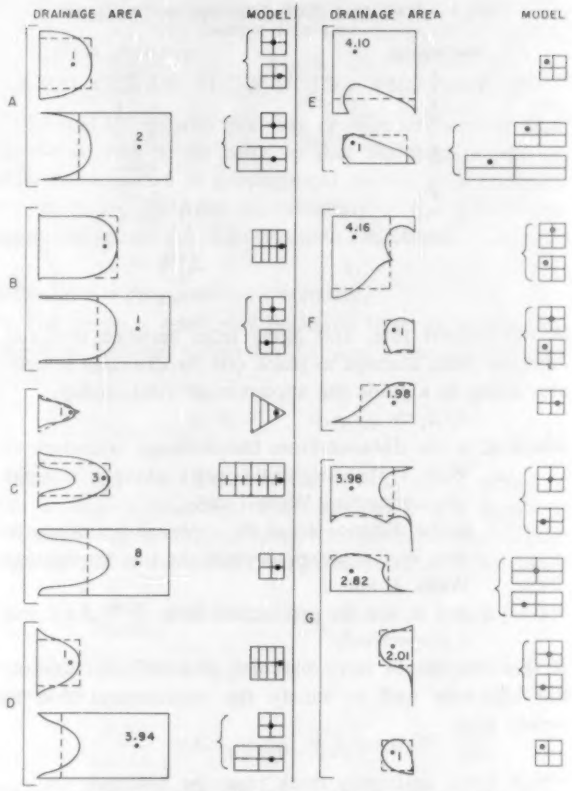


FIG. 6 — MODELS FOR ASYMMETRIC DRAINAGE AREAS.

The squaring-up method is a more time-consuming method than would ordinarily be used in computing the pressure in a reservoir containing many wells; for most purposes a satisfactory estimate of a reasonable prototype can be made by inspection of sketched-in drainage areas.

Estimation of Drainage Boundaries

Results obtained during the present study formed the basis for an investigation into a method for estimating shapes of drainage boundaries. Straight lines were drawn from each well center to adjacent well centers, and along any line the distance from the drainage boundary to each well was measured. The ratio of these distances was then compared with the ratio of flowing rates as shown in Fig. 7. Although the straight-line relation shown there is not satisfied in all cases, it may be seen that as an approximation it may be considered a good working rule.

Between any two wells there may, however, be more than one drainage boundary. In general when a portion of the drainage area of one well lies between two other wells, it is the area of the high-rate well between the two lowest-rate wells. Therefore, in sketching-in drainage areas, one should first start with the well producing

TABLE 3 — FRACTIONAL FLOW RATES PER UNIT THICKNESS NINE-WELL SYSTEM

Well Number	$(q_i/h_i)/(\Sigma q_i/h_i)$
1	0.054
2	0.202
3	0.274
4	0.150
5	0.050
6	0.058
7	0.066
8	0.045
9	0.101
	1.000

at the highest rate, and along lines between this and adjacent wells attempt to block out the drainage boundary, using as a guide the approximate relationship,

$$d_1/d_i \simeq q_1/q_i,$$

where d_1 is the distance from the drainage boundary to Well 1 (the high-rate well) along a straight line connecting Wells 1 and i

d_i is the distance from the drainage boundary to any Well i along the straight line connecting Wells 1 and i

q_1 and q_i are the production rates of Wells 1 and i, respectively.

If this first "block out" does not give sufficient area to the high-rate well to satisfy the requirement that at steady state

$$v_1/v_t = q_1/\Sigma q_i,$$

which for a uniformly thick reservoir becomes

$$A_1/A_t = q_1/\Sigma q_i,$$

then the drainage area must be adjusted to "finger" between wells. On the basis of present work it would appear that the fingering would tend to take place between the lowest-rate wells adjacent to this well. Alternatively, if there is an undrilled or sparsely drilled portion of the reservoir, the fingering would tend to be in that direction.

Using these suggestions one can approximately rather well all the drainage areas which have been studied up to this time.

As an example of the drainage boundaries that might be encountered in a reservoir a study of a nine-well

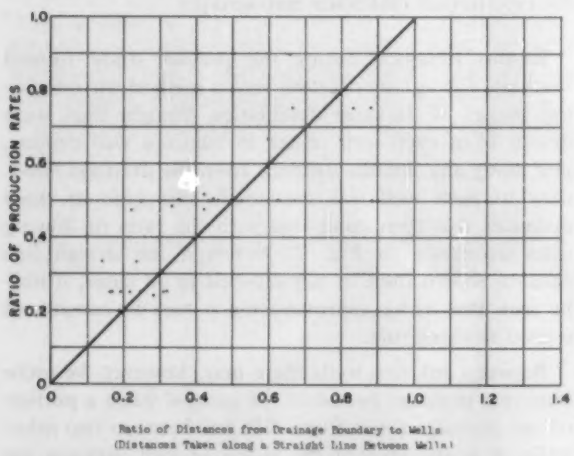


FIG. 7 — RELATION OF PRODUCTION RATE TO DRAINAGE BOUNDARY DISTANCE.

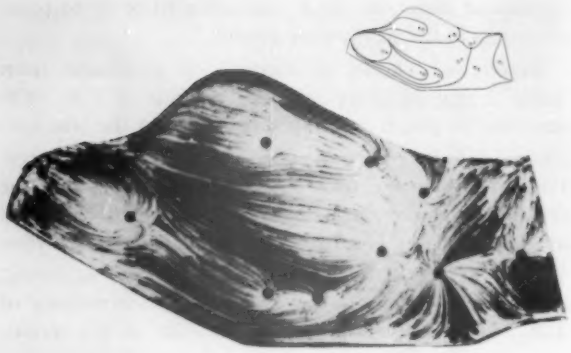


FIG. 8 — NINE-WELL RESERVOIR.

system is presented. The shape of the field selected represents a typical reservoir. Using rotameters, the fractional flowing rates were adjusted to conform approximately to the values given in Table 3. A photograph of the flowlines as well as a sketch of the field with the drainage boundaries is given in Fig. 8.

SYMBOLS

A_i = drainage area of Well i, cm²

A_t = drainage area of all wells in a reservoir, cm²

c = coefficient of compressibility of fluid at reservoir temperature, atm^{-1}

f = hydrocarbon-filled porosity, fraction, defined by

f = (total porosity) (1 − fraction interstitial water)

h = net thickness of a uniform reservoir, cm

h_i = net thickness of reservoir in drainage area of Well i, cm

k = permeability of formation, darcy

p = pressure, atm

p_o = initial reservoir pressure, atm

$\bar{p}$ = average pressure inside drainage volume of a well, atm

p^* = pressure obtained by straight-line extrapolation to $\Delta t = \infty$ of first linear portion of plot of wellbore pressure versus log $[\Delta t/(t + \Delta t)]$, atm

q = volume flow rate of a well, cc/sec measured at prevailing reservoir conditions

q_i = volume flow rate of Well i, cc/sec measured at prevailing reservoir conditions

Σq_i = total volumetric flow rate from the reservoir, cc/sec measured at prevailing reservoir conditions

t = corrected time of production of a well, seconds, defined by

$$t = \frac{\text{total fluid produced}}{\text{rate of production just before shutting in}}$$

Δt = closed-in time of a well, seconds

v_i = drainage volume of Well i, cm³ of matrix and pores

v_t = total volume of reservoir, cm³ of matrix and pores

μ = viscosity, centipoise

log = logarithm to base 10

CONCLUSIONS

It is concluded that the method given in T.P. 3876 is of sufficient accuracy for calculating the pressure distribution in a reservoir at steady state. In that paper it was also shown for particular cases that this method is of adequate accuracy prior to steady state, and hence it is believed that the method may be used in practice with some confidence. Suggestions given herein for estimation of shapes of drainage areas at steady state and for "squaring-up" these shapes should be of help in practical applications.

REFERENCES

1. Matthews, C. S., Brons, F., and Hazebroek, P.: "A Method for Determination of Average Pressure in a Bounded Reservoir," *Trans.* AIME (1954) **201**, 182.
2. Moore, A. D.: "Soap-Film and Sandbed-Mapper Techniques," *J. App. Mech.* (1950) **17**, 291.
3. Southwell, R. V.: *Relaxation Methods in Theoretical Physics*, The Clarendon Press, Oxford, 1946.

APPENDIX

ANALYSIS OF FLOW-MODEL PHOTOGRAPH

To find the relative pressure drop in any square such as 5-6 in Fig. 3, we consider that the average rate of flow through 5-6 is proportional to the area enclosed by the flow tube from the boundary of the field to the center of square 5-6. Call this area Σa_{56}. Then

$$q_{56} = b\Sigma_{56}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}1)$$

where b is a proportionality constant.

The pressure drop may be found from an analysis of the flow between a free surface and a flat plate which gives

$$\Delta p_{56} = \frac{q_{56}\mu\Delta x}{k(h\Delta x)} = \frac{q_{56}\mu}{kh}, \quad . \quad . \quad . \quad . \quad (A\text{-}2)$$

where h is the thickness of the flowing layer, which is the analog of reservoir thickness, and k is a constant which is the analog of reservoir permeability. Using Equation A-1 and rearranging Equation A-2, we have

$$\frac{\Delta p_{56}}{b\mu/kh} = \Sigma a_{56}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}3)$$

similarly the relative pressure drop in square 6-7 is given by

$$\frac{\Delta p_{67}}{b\mu/kh} = \Sigma a_{67} = \Sigma a_{56} + (\text{chord } 6)^2.$$

By the term "chord" is meant the width of the flow tube at the indicated position. Σa_{67} is the area enclosed by the flow tube from the corner to the middle of square 6-7. It is conveniently approximated as indicated above as the preceding area to the middle of square 5-6 plus the length of chord 6 squared. A typical calculation of the relative pressure drops is shown in Table A. Relative pressure drops are given in column 4. After the pressure drops in each curvilinear square are calculated, the pressures at each chord relative to a pres-

TABLE A — CALCULATION OF PRESSURE FROM FLOW MODEL

(1) Chord No.	(2) Length[a] (64th of inch)	(3) (Length)²	(4) Σ(3) Down = $\Delta p/(b\mu/kh)$	(5) Σ(4) Up = $\Delta p/(b\mu/kh)$
			133	130058
1	6.0	36	169	129925
2	7.0	49	218	129756
3	8.5	72	290	129538
4	9.5	90	380	129248
5	10.5	110	490	128868
6	11.5	132	622	128378
7	13.5	182	804	127756
8	15.5	240	1044	126952
9	18.5	342	1386	125908
10	21.0	441	1827	124522
11	24.5	600	2427	122695
12	26.0	676	3103	120268
13	27.0	729	3832	117165
14	26.5	702	4534	113333
15	27.0	729	5263	108799
16	27.5	756	6019	103536
17	27.5	756	6775	97517
18	27.0	729	7504	90742
19	25.5	650	8154	83238
20	23.0	529	8683	75084
21	19.5	380	9063	66401
22	16.0	256	9319	57338
23	12.5	156	9475	48019
24	10.0	100	9575	38544
25	7.5	56	9631	28969
26	5.5	30	9661	19338
27	4.0	16	9677	9677
Well-Circle				0000

[a]Original from which Fig. 3 is reproduced was approximately 7.3 inches on the edge.

Note: To obtain the entire area of the stream tube it is necessary to add the area enclosed by the stream tube from the corner to the dotted line in Fig. 3 to the sum of the lengths of all chords squared. This addition is made as the first entry in column 4.

sure of zero at the well-circle are obtained by summing the pressure drops outward from the well-circle. This is done in column 5, Table A.

The pressure analysis method just discussed gives relative pressure in all tubes based on a datum pressure of zero at the particular well-circle at which the flowlines terminate. As mentioned before, the datum pressure is arbitrary in this steady-state period. However, each well-circle will not in general be at the same pressure. To adjust the well-circle pressures to the correct level, first note that some equipressure lines traverse parts of both drainage areas in Fig. 4. Let p_4 be the value of the pressure found in area 4 for this equipressure line and p_1 the value found in area 1. Then if $(p_4 - p_1)$ is added to all pressures in area 1, all pressures in the entire figure will have the same datum level (i.e., $p = 0$ along well-circle 4 in Fig. 4). In practice, averages along several equipressure lines are used in determining this additive constant $(p_4 - p_1)$. Equipressure values obtained in this manner are shown in Fig. 4.

To express the pressures in a dimensionless ratio, we note that the relative pressure at any point k is given by

$$\frac{p_k}{b\mu/kh} = A_k, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(A-4)}$$

where A_k is the value obtained at chord k in the outward summation in column 5, Table A.

Now the total flow rate, q_1, in drainage area 1, Fig. 4, is given by

$$q_1 = bA_1, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}5)$$

where A_1 is the drainage area of Well 1. Substituting $(A\text{-}5)$ into $(A\text{-}4)$ gives

$$\frac{p_k}{q_1\mu/kh} = \frac{A_k}{A_1}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}6)$$

or

$$\frac{p_k}{q_1\mu/4\pi kh} = \left[\frac{4\pi}{A_1}\right] A_k \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A\text{-}7)$$

Thus the dimensionless pressure at every point as given by Equation A-7 can be obtained by multiplying each value in column 5, Table A, by 4π and dividing by the total drainage area of that well. In practice this conversion to dimensionless units is made only after average pressure results are obtained. ★★★

CALCULATION of UNSTEADY-STATE GAS FLOW WITHIN a SQUARE DRAINAGE AREA

JIM DOUGLAS, JR.
D. W. PEACEMAN
H. H. RACHFORD, JR.
JUNIOR MEMBERS AIME

HUMBLE OIL & REFINING CO.
HOUSTON, TEX.

T. P. 4165

ABSTRACT

The problem of unsteady-state gas flow through porous media has been solved numerically only for the case of linear or radially symmetric reservoirs. A recently introduced numerical method for solving the unsteady-state heat flow equation in two dimensions is applied to the calculation of the depletion of a square region containing a perfect gas. Solutions are presented in graphical form for various values of dimensionless parameters. The solutions are compared with published solutions for radial reservoirs.

INTRODUCTION

The problem of unsteady-state flow of gas through porous media gives rise to a second-order non-linear partial differential equation for which no analytical solution has been found. Numerical approximations to solutions of the gas flow problem have been obtained by the stepwise solution of an associated difference equation[1,2]. However, the methods so far developed have required that the reservoir be either linear or radially symmetric. This restriction in shape has been necessary so that only two independent variables be considered, namely, one distance variable and time. In order to deal with reservoirs having more realistic shapes, it is necessary to develop numerical procedures for the solution of the gas flow problem involving two distance variables.

A numerical procedure, denoted as the alternating-direction implicit method, for the solution of the heat-flow problem in two dimensions has recently been introduced[3]. By the use of this procedure, approximate solutions have been obtained for heat-flow problems in a square[3], and in regions having various non-rectangular boundaries[4]. Because of the similarity between the equation for heat conduction in solids and the equation for gas flow in porous media, it is reasonable to expect that the alternating-direction implicit method should also be useful for solving the gas flow problem in various two-dimensional regions.

Solutions have been calculated for the simplest two-dimensional region, a square reservoir with a single well in the center. While reservoirs of such simple geometry seldom, if ever, exist, the solution of this problem is of some practical importance because it is also the solution of another problem, that of determining the depletion history about an individual well in an infinite uniform reservoir containing wells spaced throughout on a square lattice and producing equally from each well. Finally, it is of interest to compare solutions for a square reservoir with those for a circular reservoir and to determine the effect of the shape of the boundary for that particular case.

METHOD OF CALCULATION

Basic Differential Equation

By combining the equation of continuity,

$$\nabla \cdot (\gamma \vec{v}) = -\phi \frac{\partial \gamma}{\partial \theta}, \quad \ldots \ldots \quad (1)$$

the perfect gas law,

Prepared for presentation at the University of Michigan Research Conference on the Flow of Natural Gas from Reservoirs, June 30-July 1, 1955.
Paper presented at Joint Meeting of Rocky Mountain Petroleum Section in Denver, May 26-27, 1955. Manuscript received in Petroleum Branch office on May 16, 1955.
[1]References given at end of paper.

$$\gamma = \frac{p}{RT}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and Darcy's law,

$$\vec{v} = -\frac{K}{\mu} \nabla p, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

the basic differential equation for flow of a perfect gas in a homogeneous porous medium,

$$\nabla^2 p^2 = \frac{2\phi\mu}{K} \frac{\partial p}{\partial \theta}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

is obtained. In a reservoir of constant thickness, only two space variables need be considered, and Equation 4 reduces to

$$\frac{\partial^2 p^2}{\partial x^2} + \frac{\partial^2 p^2}{\partial y^2} = \frac{2\phi\mu}{K} \frac{\partial p}{\partial \theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The initial condition for the problem is

$$\theta = 0, p = p_o, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

while the boundary equations, corresponding to the condition of no flow across the outer boundaries of the square, are

$$x = \pm L, \frac{\partial p}{\partial x} = 0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$y = \pm L, \frac{\partial p}{\partial y} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The well, located at the center of the square, is assumed to be of negligible diameter, compared with the dimensions of the reservoir. The rate of production, q, of gas into the well is assumed constant.

Dimensionless Differential Equation

By making the substitutions

$$P = \frac{p}{p_o}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$X = \frac{x}{L}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$Y = \frac{y}{L}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$\Theta = \frac{p_o K \theta}{L^2 \phi \mu}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$Q = \frac{-\frac{dN}{d\Theta}}{N_o} = \frac{q\mu RT}{4p_o^2 Kt}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where N is the number of mols remaining in the reservoir at any time, Equation 5 is reduced to dimensionless form

$$\frac{\partial^2 P^2}{\partial X^2} + \frac{\partial^2 P^2}{\partial Y^2} = 2\frac{\partial P}{\partial \Theta}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The dimensionless rate parameter, Q, is sufficient to characterize the problem. It is defined so that $Q\Theta$ represents the fraction of the original gas which has been removed.

For convenience in carrying out the numerical integration, Equation 14 may be transformed into a quasi-linear partial differential equation by the following change of dependent variable:

$$U = P^2; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

then,

$$\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} = \frac{1}{U^{1/2}} \frac{\partial U}{\partial \Theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

The initial and boundary conditions become

$$\Theta = 0, U = 1, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

$$X = \pm 1, \frac{\partial U}{\partial X} = 0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$Y = \pm 1, \frac{\partial U}{\partial Y} = 0. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Difference Equation

The numerical solution of Differential Equation 16 may be obtained by replacing the continuous derivatives by ratios of finite differences and solving the resulting difference equations. It has been shown[6,8] that the alternating-direction implicit method may be used for the solution of the heat flow equation,

$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} = \frac{\partial T}{\partial \Theta}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

in various two-dimensional regions. Because of the similarity between Equations 16 and 20, it is intuitively clear that the same numerical procedure should be useful for integrating Equation 16. Using this procedure, the following two difference equations are obtained:

$$\frac{W_{i-1,j,2n+1} - 2W_{i,j,2n+1} + W_{i+1,j,2n+1}}{(\Delta X)^2} + \frac{W_{i,j-1,2n} - 2W_{i,j,2n} + W_{i,j+1,2n}}{(\Delta Y)^2} = \frac{1}{W^{1/2}_{i,j,2n}} \frac{W_{i,j,2n+1} - W_{i,j,2n}}{\Delta\Theta_{2n}}, \quad . \quad . \quad . \quad . \quad (21)$$

$$\frac{W_{i-1,j,2n+1} - 2W_{i,j,2n+1} + W_{i+1,j,2n+1}}{(\Delta X)^2} + \frac{W_{i,j-1,2n+2} - 2W_{i,j,2n+2} + W_{i,j+1,2n+2}}{(\Delta Y)^2} = \frac{1}{W^{1/2}_{i,j,2n+1}} \frac{W_{i,j,2n+2} - W_{i,j,2n+1}}{\Delta\Theta_{2n+1}}. \quad . \quad . \quad . \quad (22)$$

where i, j, and n are the indices in the X-, Y-, and Θ-directions, respectively, and $W_{i,j,n} = W(i\Delta X, 1 - j\Delta Y, \Theta_n)$, $\Theta_n = \sum_{k=0}^{n-1} \Delta\Theta_k$. Equation 21 is used at odd-numbered time steps to proceed from Θ_{2n} to Θ_{2n+1} and Equation 22 is used at even-numbered time steps to proceed from Θ_{2n+1} to Θ_{2n+2}. Equation 21 is said to be implicit in the X-direction since it contains three unknown values of W along a line parallel to the X-axis; similarly, Equation 22 is said to be implicit in the Y-direction. It is necessary that the two time intervals constituting a pair be equal in order for the method to be stable. Thus

$$\Delta\Theta_{2n} = \Theta_{2n+1} - \Theta_{2n} = \Delta\Theta_{2n+1} = \Theta_{2n+2} - \Theta_{2n+1} \quad . \quad (23)$$

However, it is not necessary for the time intervals of one pair to be equal to the time intervals of another pair.

The change in dependent variables from U in Equation 16 to W in Equations 21 and 22 reflects the fact that the solution of the difference equations is an approximation to the solution of the differential equation. Douglas[6] has shown for the application of the alternating-direction implicit method to the heat flow problem that, as ΔX, ΔY, and $\Delta\Theta$ are decreased, the solution of the difference equations converges to that of the differential equation. Stability and convergence have not been demonstrated for Equations 21 and 22, which result from application of the method to a quasi-linear differential equation. However, for the case of quasi-linear differential equations in one dimension, it has been shown[3] that if an implicit difference equation is set up in which the non-constant multipliers of the derivatives are replaced by their values at the known time level, numerical procedures are obtained which are stable and convergent. Consequently, a similar procedure is followed here, wherein $1/U^{1/2}$ is replaced by

$1/W^{1/2}_{1,j,2n}$ and $1/W^{1/2}_{1,j,2n+1}$ in the two difference equations.

Equations 21 and 22 lead to systems of simultaneous equations which can be solved directly without iteration. Each set of simultaneous equations corresponds to a line of points in the integration net, and contains as many equations and unknowns as there are points in the line. The details of the procedure for solving such systems of equations have been given elsewhere.[5,6,8]

Because of symmetry it is sufficient to carry out the integration in only one-eighth of the square. Consequently, it is possible to calculate the pressure distribution in the square with many fewer points in the integration net. The integration net covers the region bounded by the lines $X = 0$, $Y = 1$, and $X = Y$, with the well located at the point $(0,0)$. The mesh widths are set equal to each other such that

$$\triangle X = \triangle Y = \frac{1}{M},$$

where M is the number of intervals along the center lines. The indices i and j are chosen so that they are 0 at the point $(0,1)$ with i increasing to the right and j increasing in the downward direction. The following boundary difference equations are obtained from the condition that the solution is symmetric with respect to each of the three boundary lines:

$$X = 0,\ W_{-1,j} = W_{1,j} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

$$Y = 1,\ W_{i,-1} = W_{i,1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

$$X = Y,\ W_{i,M-i-1} = W_{i+1,M-i} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

It remains to write an equation corresponding to production into the well. This is done by assuming production is into a square whose corners lie at the points $\pm\triangle x/2$, $\pm\triangle y/2$. The flow across any horizontal line of length $\triangle x$ is

$$\triangle q = -\frac{Ktp}{\mu RT}\frac{\partial p}{\partial y}\triangle x = -\frac{Kt}{2\mu RT}\frac{\partial p^2}{\partial y}\triangle x. \quad . \quad . \quad (27)$$

In dimensionless form, this becomes

$$\triangle Q = -\frac{1}{8}\frac{\partial U}{\partial Y}\ \triangle X. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

The flow across the upper edge of the square, which is equal to one-fourth of the total flow into the square, may be approximated by the following difference equation:

$$\frac{Q}{4} = \frac{1}{8}\frac{W_{0,M-1} - W_{0,M}}{\triangle Y}\triangle X. \quad . \quad . \quad . \quad . \quad . \quad (29)$$

Since $\triangle X = \triangle Y$, the final boundary difference equation is

$$W_{0,M-1} - W_{0,M} = 2Q \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

Equations 24, 25, 26, and 30 are combined with difference Equations 21 and 22 to eliminate values of W at points outside the region of integration. The equations so formed contain only two unknowns and always constitute either the first or last member of a set of simultaneous equations corresponding to a line. The equation which relates the values of W at the intersection of each line with the diagonal always involves an unknown value of W on the longer adjacent line as a result of Equation 26. This value of W may always be obtained by arranging the calculations so that the long lines are solved before the short ones. A more complete discussion of handling this type of boundary is given elsewhere.[6]

Calculations

Calculations were carried out for three values of the rate parameter Q. Because of the small internal memory of the electronic computer used, only 35 points were used in the integration net, corresponding to $M = 7$. In each case, the size of the first time increment used was $\triangle\Theta_0 = 0.00005/Q$; the second time increment was, of course, equal to the first. Thereafter, each odd time increment was obtained by multiplying each previous odd time increment by 1.25.[5] Thus

$$\triangle\Theta_{2n} = \triangle\Theta_{2n+1} = 1.25\ \triangle\Theta_{2n-2} = 1.25\ \triangle\Theta_{2n-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

After $Q\Theta$ reached 0.0625, $Q\triangle\Theta$ was kept constant at 0.00625 until the end of the problem. Calculations were continued until a negative value of $W_{0,M-1}$ was obtained.

The values of Q used were $0.01(\pi/8)$, $0.05(\pi/8)$, and $0.1(\pi/8)$. The reason for using these values will become apparent in the discussion of a comparison with the radial system.

In order to provide a check on the accuracy of machine operation, a quadrature was calculated using the trapezoidal rule to determine the average value of the pressure at the end of each even time step. Agreement between the average pressure decline and $Q\Theta$ was within 1½ per cent for all the results. Closer agreement would require using a finer net for the calculation and a better rule for the quadrature.

RESULTS

Because of the number of independent variables involved in a non-linear unsteady-state problem in two dimensions, the task of presenting a complete solution, either as graphs or tables, is a formidable one. In the present case, there are four independent variables, Q, X, Y, and Θ. Fortunately, it has been possible to arrive at an approximate correlation which presents the calculated results in compact form; this is presented in the next section. In this section only a small sample of the calculated solutions are presented.

One way of presenting the solutions is by means of a set of isopiestic maps, one for each combination of Q and Θ. Figs. 1 and 2 are two such maps for two different times at the highest rate, i.e., $Q = 0.1(\pi/8)$. Fig. 1 corresponds to 1.1 per cent depletion of the gas, while Fig. 2 corresponds to 60 per cent depletion.

The contours were obtained by determining the set of X and Y for which pressures are the same by plotting a function, $f(P)$, vs X for all values of Y and obtaining the X-values of intersections of lines of constant $f(P)$ with each of the curves $Y = 0$, 1/7, 2/7, . . . 1. As the values of P are quite close together near the corner (1,1), it was necessary that the function plotted be sensitive to small changes in values of P in this region. For this purpose the function chosen was

$$f(P) = \frac{1}{2 - \dfrac{ln(P_a/P)}{ln(P_a/P_c)}} \quad , \quad . \quad . \quad . \quad . \quad . \quad (32)$$

where P_a is the average value of the pressure at the time considered, and P_c is the value of the pressure in the corner, $X = Y = 1$.

It is of interest to examine a portion of the isopiestic map for the associated problem, that of an infinite uniform gas reservoir containing wells spaced throughout on a square lattice. This is shown in Fig. 3. There is some resemblance between the pattern observed here and the pattern deduced for the five-spot problem.[7] However, the pattern observed here is considerably less symmetrical than that for the steady-state problem.

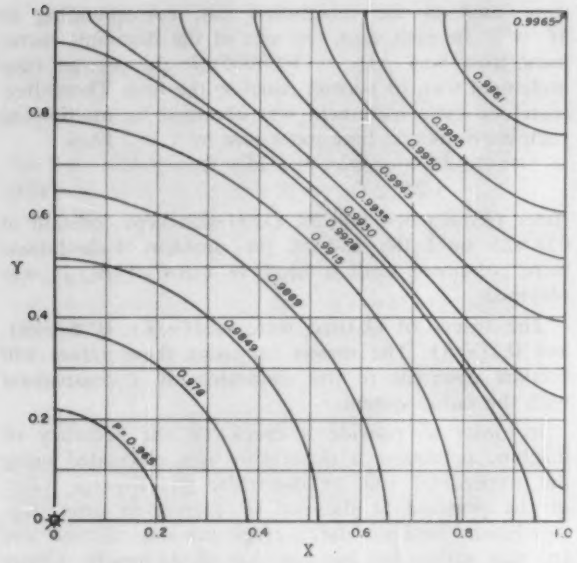


FIG. 1 — ISOPIESTIC MAP FOR DEPLETION OF SQUARE GAS RESERVOIR. $Q = 0.1\ (\pi/8)$, $Q\Theta = 0.01097$.

A second method of presenting the solutions is by use of a set of pressure profiles along various lines. Each graph is a family of curves of pressure vs position along the line for various values of time, there being one such family of curves for each line examined at each rate. Such graphs have the advantage of showing more directly than isopiestic maps how the pressure declines with time at various points. Figs. 4 and 5 are two such graphs drawn for the diagonal, corresponding, respectively, to the highest rate calculated $Q = 0.1\ (\pi/8)$, and to the lowest rate $Q = 0.01\ (\pi/8)$. The use of a logarithmic scale for the abscissa reduces the curvatures of the various pressure profiles considerably; furthermore it removes the necessity for attempting to plot the pressure at the center of the square. This is desirable, since the difference equations produce a

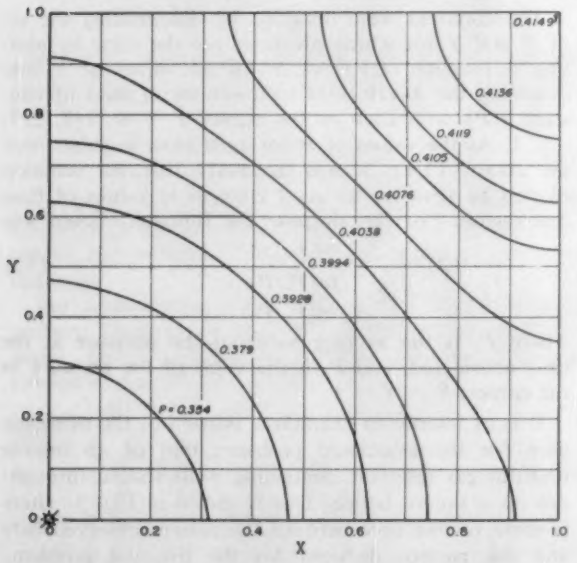


FIG. 2 — ISOPIESTIC MAP FOR DEPLETION OF SQUARE GAS RESERVOIR. $Q = 0.1\ (\pi/8)$, $Q\Theta = 0.6$.

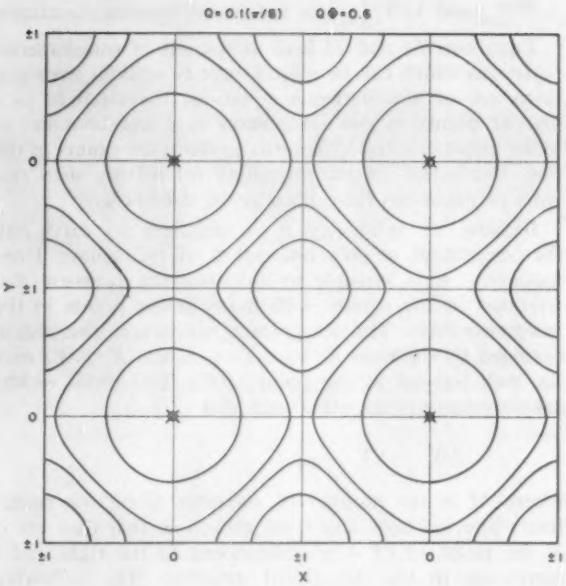


FIG. 3 — ISOPIESTIC MAP FOR DEPLETION OF AN INFINITE GAS RESERVOIR CONTAINING WELLS ON A SQUARE LATTICE.

number at that point having little significance. To estimate wellbore pressure, it is necessary to extrapolate P^2 on a logarithmic plot to the radius of the well bore. The circled points in Figs. 4 and 5 are discussed below in the section Comparison with Radial Solution.

UNIVERSAL ISOPIESTIC MAP

Examination of Figs. 1 and 2 discloses a remarkably close resemblance between the shapes of the isobars of the two maps. While the pressure changes markedly with time at each point, the shape of the isobar passing through any given point changes very little with time. Furthermore, comparison between such maps drawn for the various rates calculated at equal fractions of gas depleted shows that there is even less change in shape of the curves with rate than there is with time. However, comparison with maps for less than 1 per cent withdrawal did show considerable deviation in the shapes of the curves. On the basis of the above, it is concluded that, after more than 1 per cent of the gas has been withdrawn, the shape of the isobar passing through any given point is practically invariant with time and rate.

It is a consequence of this conclusion that there exists a universal isopiestic map which may be used to reduce greatly the number of curves necessary to describe the complete solution. Such a map could be used in conjunction with graphs similar to Figs. 4 and 5 to determine P for any set of values of X, Y, Θ and Q. One would locate the point (X, Y) on the map, follow the curve passing through that point to the diagonal, read the corresponding value of X_d, and use this value of X_d on one of the diagonal pressure profile curves, corresponding to the desired values of Q and Θ, to obtain the pressure, P.

COMPARISON WITH RADIAL SOLUTION

It is expected that Figs. 4 and 5 should be similar to published solutions for the radial gas flow problem,[2] in which pressure is plotted against radius for various values of Q and Θ. Two questions arise: what is the

relationship between Q for the radial case and Q for the square case; and, what is the relationship between radius and position along the diagonal?

To answer the first question, it is assumed that it is desired to compare a circle and a square of equal area, and to compare solutions at equal values of q. If the dimensionless rate for the radial case be designated as Q_r, then[2]

$$Q_r = \frac{2\,q\,\mu\,RT}{\pi\,p_0^2\,Kt}. \quad \ldots\ldots\ldots \quad (33)$$

Combining with Equation 13 yields

$$Q = \frac{\pi}{8}\ Q_r \quad \ldots\ldots\ldots\ldots \quad (34)$$

Thus values for Q for calculating the square case were chosen so that the solutions obtained could be compared with solutions for the radial case corresponding to $Q_r = 0.1$, 0.05, and 0.01.

Determining the relationship between radius and position along the diagonal is a somewhat more difficult problem. It is proposed that the universal isopiestic map be used to establish this relationship by hypothesizing that any isobar has the same pressure as that given by the radial solution for the circle of equal area. Then the position on the diagonal where the isobar intersects it is equivalent to the radius of that circle. The areas enclosed by the curves of several isopiestic maps were measured, and the radii of the circles of equal areas were plotted as a function of the intersection on the diagonal in Fig. 6. The dotted line and curve are asymptotes which are derived from the assumption that the isobars are circles centered, in one case, at the well, and, in the other case, at the corner.

Using Fig. 6 and the solution for the radial case,[2] pressures were calculated for various positions along the diagonal and are plotted as circled points in Figs. 4 and 5. In all cases, the deviation in P is less than 1½ per cent of the pressure decline.

Approximate Method

On the basis of the above comparison, it is possible now to set up a very compact approximate solution to the problem of depletion of gas from a square. In addition to the published radial solutions, it is necessary to have only one figure, a universal isopiestic map

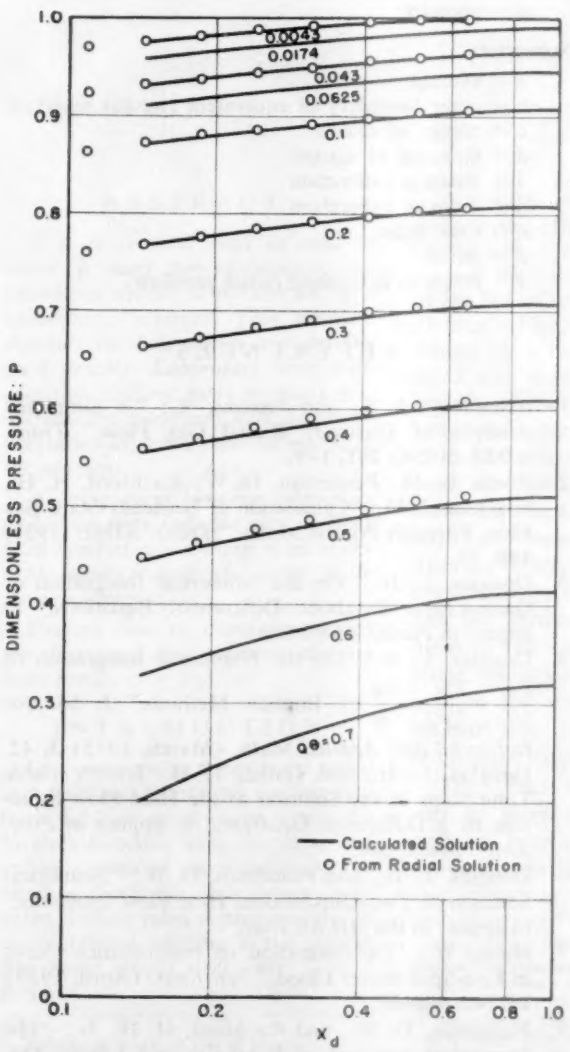


Fig. 4 — Pressure Profile Along Diagonal for Depletion of Square Gas Reservoir. $Q = 0.1\ (\pi/8)$.

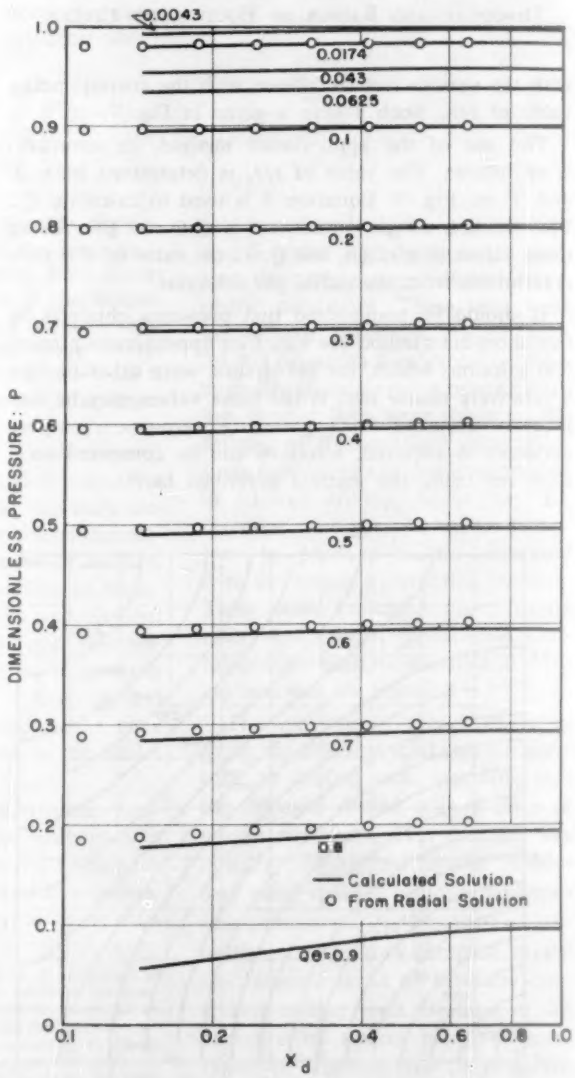


Fig. 5 — Pressure Profile Along Diagonal for Depletion of Square Gas Reservoir. $Q = 0.01\ (\pi/8)$.

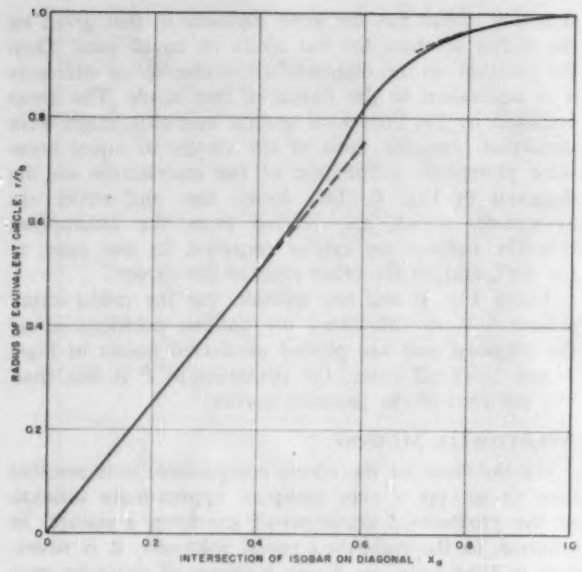


FIG. 6 — RELATIONSHIP BETWEEN POSITION ON DIAGONAL AND RADIUS OF EQUIVALENT CIRCLE.

with the various isobars labeled with the corresponding value of r/r_b. Such a map is given in Fig. 7.

The use of the approximate method, in summary, is as follows. The value of r/r_b is determined from X and Y on Fig. 7. Equation 3 is used to calculate Q_r. The fraction of gas withdrawn is $Q_r\Theta_r = Q\Theta$. Using these values of r/r_b, Q_r, and $Q_r\Theta_r$, the value of P is then determined from the radial gas solutions.[2]

It should be emphasized that pressures obtained by this short-cut method are based on approximate numerical solutions which, for the square, were calculated on a relatively coarse net. While these values may be sufficiently accurate for engineering purposes, if higher accuracy is required, solutions can be computed on a finer net using the method described herein.

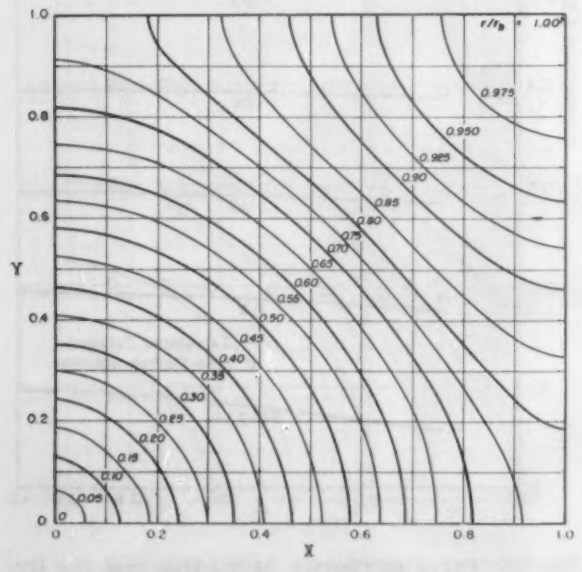


FIG. 7 — UNIVERSAL ISOPIESTIC MAP.

NOMENCLATURE

K = permeability
L = half the side of square reservoir
M = number of increments in distance L
N = mols of gas in reservoir
P = dimensionless pressure, defined by Equation 9
p = absolute pressure
Q = dimensionless rate, defined by Equation 13
q = rate of production, mols per unit time
R = gas constant
r = radius in equivalent circular reservoir
T = absolute temperature
t = thickness of reservoir
$U = P^2$, solution of Differential Equation 16
v = velocity
$W = P^2$, solution of Difference Equations 21 and 22
X = dimensionless distance, defined by Equation 10
x = distance
Y = dimensionless distance, defined by Equation 11
y = distance in direction perpendicular to x-axis
γ = mol density
Θ = dimensionless time defined by Equation 12
θ = time
μ = viscosity
ϕ = porosity

Subscripts

a = average
b = outer boundary of equivalent circular reservoir
c = corner of square
d = diagonal of square
i = index in x-direction
j = index in y-direction
n = time index
o = initial
r = refers to equivalent radial problem

REFERENCES

1. Aronofsky, J. S., and Jenkins, R.: "A Simplified Analysis of Unsteady Radial Gas Flow," *Trans.* AIME (1954) **201,** 149.
2. Bruce, G. H., Peaceman, D. W., Rachford, H. H., and Rice, J. D.: "Calculation of Unsteady-State Gas Flow Through Porous Media," *Trans.* AIME (1953) **198,** 79.
3. Douglas, J., Jr.: "On the Numerical Integration of Quasi-Linear Parabolic Differential Equations," to appear in *Pacific J. of Math.*
4. Douglas, J., Jr.: "On the Numerical Integration of $\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = \frac{\partial u}{\partial t}$ by Implicit Methods," *J. Soc for Industrial and Applied Math.* (March, 1955) **3,** 42.
5. Douglas, J., Jr., and Gallie, T. M., Jr.: "Variable Time Steps in the Solution of the Heat Flow Equation by a Difference Equation," to appear in *Proc. Amer. Math. Soc.*
6. Douglas, J., Jr., and Peaceman, D. W.: "Numerical Solution of Two-Dimensional Heat Flow Problems," to appear in the *AIChE Jour.*
7. Hurst, W.: "Determination of Performance Curve in Five-Spot Water Flood," *Pet. Engr.* (April, 1953) **25,** No. 4, B-40.
8. Peaceman, D. W., and Rachford, H. H., Jr.: "The Numerical Solution of Parabolic and Elliptic Differential Equations," *J. Soc. for Industrial and Applied Math.* (March, 1955) **3,** 28. ★★★

EFFECT of MUD COLUMN PRESSURE on DRILLING RATES

A. S. MURRAY
MEMBER AIME
IMPERIAL OIL LTD.
CALGARY, ALTA., CANADA

R. A. CUNNINGHAM
HUGHES TOOL CO.
HOUSTON, TEX.

T. P. 4166

ABSTRACT

If a dense fluid such as mud or water is used for circulation, the formation drilled is influenced by a hydrostatic pressure. This pressure depends on hole depth and drilling fluid density. Laboratory tests indicate that drilling rates in many formations are decreased with increased pressure—in some cases as much as 90 per cent.

A comparison between laboratory and field tests indicate that drilling fluid head affects drilling rates in the field approximately the same as in the laboratory.

Drilling rates of many formations are increased by reducing drilling fluid head.

INTRODUCTION

For many years it has been noted that field and laboratory drilling rate tests did not agree even when the formations tested were the same. For instance, tests of some shales by the Hughes Tool Co. laboratory indicated drilling rates approximately 20 to 30 ft/hour, whereas in the ground this shale would drill only 3 to 5 ft/hour.

A possible reason for this discrepancy is the effect of the high pressure which the drilling fluid exerts against the formation at the bottom of the hole. Consider a small element of rock (Fig. 1) that is to be removed by a rock bit. If the hole is filled with mud or water, the upper surface of the rock element is subjected to a pressure which depends on hole depth and fluid density. The mass of earth around this rock element presses against the circumferential surface and the lower surface. Because of the probability of shearing stresses between the rock element and the surrounding rock, this element is not under true hydrostatic stress. However, as a first approximation for test purposes the rock element was assumed to be under hydrostatic stress.

The effect of hydrostatic pressure on some physical properties of rock has been studied.[1,2,3] These tests show that the "differential" compressive stress* necessary to cause rupture in rock cylinders is greater when tested under high hydrostatic pressure than when tested under atmospheric conditions. These tests were made with pressures greater than 20,000 psi which is in excess of those normally encountered in oil well drilling. Similar tests were made by the Bureau of Reclamation[4] using pressures equivalent to those encountered in oil well drilling. Again the "differential" compressive stress necessary to produce failure increased with increasing hydrostatic pressure. These tests indicated that drilling rates would probably decrease. Correlation between these tests and drilling tests was not practical.

The purpose of this work is to study the effect of mud column pressure on drilling rate, assuming that the material drilled is in a state of hydrostatic stress. This problem was initially investigated in the laboratory using variable bit loads and confining pressures. Confirmation of laboratory results was obtained in the field from a series of carefully controlled drilling tests. Because of the necessity of testing many different types of formations, only results from representative formations will be presented here.

[1]References given at end of paper.

Paper presented at Petroleum Branch Fall Meeting in New Orleans, Oct. 2-5, 1955. Manuscript received in Petroleum Branch office on July 13, 1955.

*If a cylindrical specimen is subjected to hydrostatic pressure on all surfaces, the specimen is in a state of hydrostatic stress. If an additional axial load is applied at the ends of the cylinder the stress caused by this loading is called differential stress. For instance, in the absence of the hydrostatic pressure but with a compressive loading, the "differential" stress is equal to the total compressive stress.

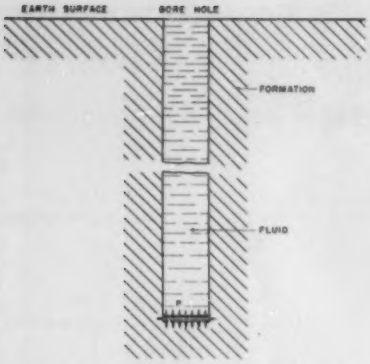


FIG. 1 — ELEMENT OF FORMATION BENEATH ROCK BIT.

NOMENCLATURE

A few terms used in this paper require explanation:

Load on bit is the net load acting to push the rock bit against the surface to be drilled.

Hydrostatic pressure refers to the pressure of the mud column at a given depth in a wellbore.

Confining pressure refers to the pressure maintained within the laboratory drilling machine. It is assumed that hydrostatic pressure in the wellbore and confining pressure in the drilling machine produce similar conditions affecting the drilling rates of rocks.

Hydrostatic stress is a three dimensional state of stress in which the three principal stresses are equal. It is assumed that the material is homogeneous and isotropic, i.e., having properties the same from point to point and the same in all directions. Under these conditions no shear stress exists, resulting in conditions similar to that of a fluid under hydrostatic pressure.

Formation names used to identify formations are local terms or names applied by the authors to designate a location, etc. For instance, "Ellenberger" dolomite and "Canadian" dolomite represent formations from two different areas.

LABORATORY EQUIPMENT

To approximate formation conditions, a machine was built which utilizes a 1¼-in. diameter rock bit so that core samples can be drilled while subjected to a uniform hydrostatic pressure. Fig. 2A shows the 1¼-in. diameter bit used for drilling samples.

Fig. 2B shows a cross section of the drilling chamber designed for high pressure drilling. Water plus a rust inhibitor is maintained at a test pressure within the confines of the drilling chamber (1) and (2). A 1¼-in. diameter rock bit (3) is mounted on a drill stem (4) within this chamber. A 2 to 5-in.-diameter by 2½-in.-long formation core (9) is mounted in a specimen holder (5). This specimen holder with the rock moves in a vertical direction. Bit load is applied by the air cylinder (8) through the connecting members (7) and (6) to the specimen holder. An additional load is applied by the pressure in the chamber pushing against the thin rods (6).

The chips formed are removed by fluid entering the vessel from an external source and moving as indicated by the arrows through the drill stem and bit. The flow is directed at the surface drilled. Circulation (see Fig. 2C) is maintained by a low-pressure high-volume pump capable of circulating 4 gal of fluid per minute. Pressure is maintained in the entire system by a high-pressure low-volume pump capable of maintaining a maximum of 14,000 psi. With this arrangement, less than ½ hp is required to circulate 4 gal/min. To circulate this volume against 10,000 psi normally requires about 25 hp. A photograph of the complete machine is shown in Fig. 2D.

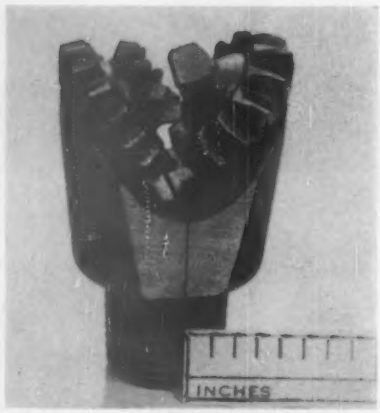
LABORATORY TEST RESULTS

Formations which have been tested in the special drilling apparatus vary from easily drilled shales to very hard-to-drill quartzites. In most cases the addition of confining pressure has caused a decrease in drilling rate.

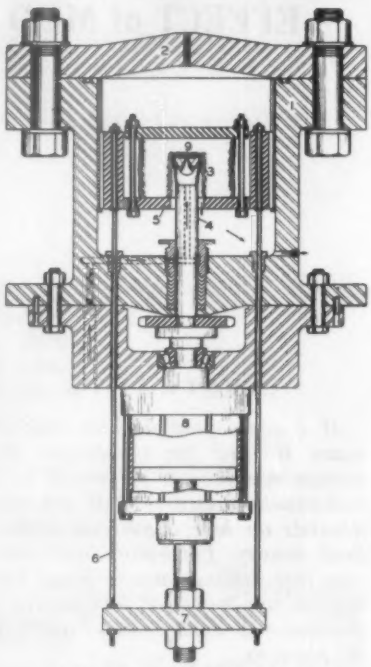
For each formation a series of tests were made in which bit load was held constant while drilling rate was determined as a function of pressure. Fig. 3 shows a plot of the complete results from one series of tests. For each pressure condition six to 12 tests were made and averaged, e.g., at 2,500 psi 10 tests were made and the average of these values is plotted as "0." Because of the large scatter, only average values were considered in describing the various curves.

DRILLING RATE AS A FUNCTION OF CONFINING PRESSURE

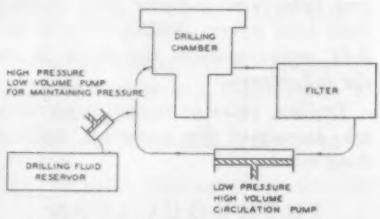
Drilling rate as a function of confining pressure is shown for seven different formations in Fig. 4A. These samples represent shales, limestones, dolomites and basalts. Four



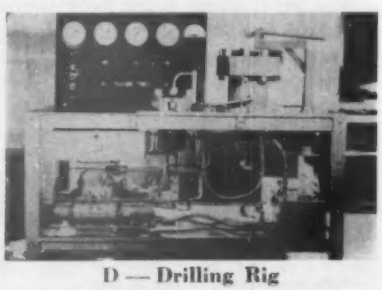
A — 1¼-In. Rock Bit



B — Pressure Chamber


DRILLING CHAMBER
HIGH PRESSURE LOW VOLUME PUMP FOR MAINTAINING PRESSURE
FILTER
DRILLING FLUID RESERVOIR
LOW PRESSURE HIGH VOLUME CIRCULATION PUMP

C — Circulation System



D — Drilling Rig

FIG. 2 — EXPERIMENTAL HIGH PRESSURE DRILLING EQUIPMENT.

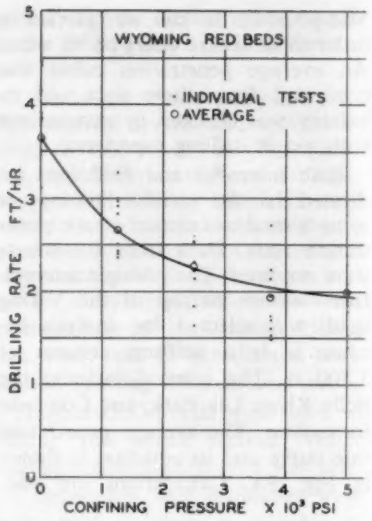


FIG. 3—DRILLING RATE VS CONFINING PRESSURE.

are actual oil field cores; three are quarry rocks. All were tested under identical conditions, i.e., constant rpm, bit load, etc. These formations are plotted together because of their apparent similarity of reaction to pressure. This is of particular interest since these seven formations vary widely in physical and chemical properties.

The data shown in Fig. 4B illustrate two results that are fairly general for this type of test.

1. A decrease in drilling rate results from increased confining pressure. A maximum is reached above which additional pressure does not further appreciably reduce drilling rate. This maximum pressure is apparently different for each formation.

2. Relatively, the drilling rates of easy-to-drill formations are more greatly affected by the increase in pressure than the harder-to-drill formations. Consider the maximum relative decrease in drilling rate as

$$\frac{R_a - R_m}{R_a}$$

Where R_a = drilling rate at atmospheric condition
R_m = drilling rate at near horizontal portion of the curve

Using this relationship, drilling rate in the Rifle shale decreased 78 per cent, Spraberry shale 76 per cent, Wyoming Red Beds 63 per cent, Pennsylvanian limestone 50 per cent. Rush Springs sandstone 33 per cent, Basalt 33 per cent, Ellenberger dolomite 22 per cent (Fig. 4A). Further illustrating this, the shale of Fig. 4B was drilled at 21.2 ft/hour at atmospheric conditions and 1.4 ft/hour at 5,000 psi, e.g.,

$$\frac{R_a - R_m}{R_a} = \frac{21.2 - 1.4}{21.2} = 93.4 \text{ per cent}$$

A characteristic common to many soft shales is shown in Fig. 4C. A relatively small confining pressure causes a large decrease in drilling rate, e.g., 500 psi — 77 per cent, 1,000 psi — 85 per cent.

Heavy bit loads (40,000 to 75,000 lb on a 9-in.-diameter bit) are required to drill many hard formations. As a result the 1,000-lb load on a 1¼-in.-diameter bit used in drilling some of the softer formations was considered inadequate for drilling harder formations. Instead, a bit load of 3,000 lb was used. The results obtained from drilling a hard, tightly cemented quartzitic material are shown in Fig. 4D. Here again drilling rate is decreased as the material is subjected to increased confining pressures.

IRREGULAR REACTIONS TO CONFINING PRESSURE

Several formations have reacted differently from those described above. Three formations (Fig. 5) illustrate these differences.

1. The drilling rate of White dolomite showed a characteristic reaction

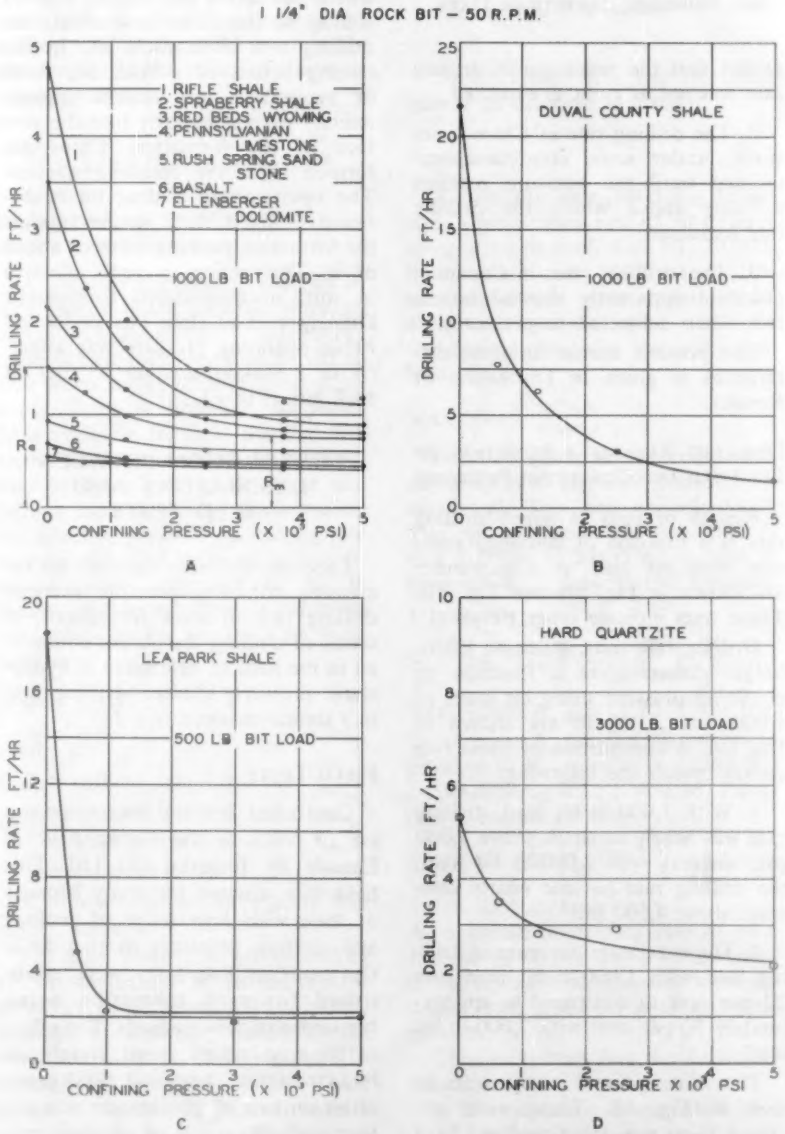


FIG. 4 — DRILLING RATE VS CONFINING PRESSURE.

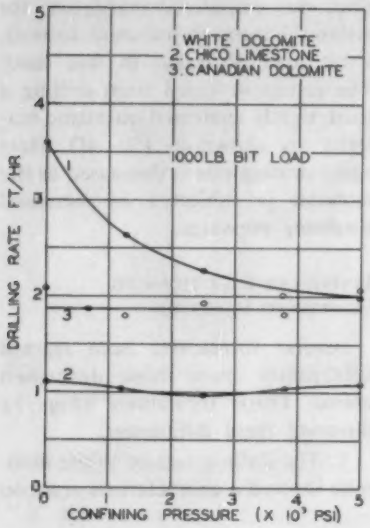


FIG. 5—DRILLING RATE VS CONFINING PRESSURE, IRREGULAR DATA.

except that the reduction in drilling rate was not as great as expected.

2. The drilling rate of Chico limestone, under some conditions, decreased until the pressure reached a value above which the drilling rate increased.

3. The drilling rate of Canadian dolomite apparently showed no effect when subjected to pressures.

One possible reason for these differences is given in Discussion of Results.

DRILLING RATE AS A FUNCTION OF BIT LOAD AND CONFINING PRESSURE

Results of tests in which drilling rate is a function of confining pressure with bit load as a parameter are shown in Fig. 6A and Fig. 6B. These tests indicate other trends.

Drilling rate tests, made on Ellenberger dolomite, as a function of confining pressure using bit loads of 1,000 and 2,000 lb are shown in Fig. 6A. A comparison of these two curves reveals the following:

1. With 1,000-lb bit load, drilling rate was nearly constant above 1,000 psi, whereas with 2,000-lb bit load, the drilling rate became nearly constant above 4,500 psi.

2. The maximum decrease in drilling rate with 1,000-lb bit load was 22 per cent as compared to approximately 50 per cent with 2,000-lb bit load.

The same general results can be seen in Fig. 6B. These were obtained from tests on a medium hard shale, Wyoming Red Beds, using bit loads of 500, 1,000, 1,500 and 2,000 lb. With 500-lb bit load, confining pressure seemed to affect drilling rate very little.

The results from Fig. 6B are replotted in Fig. 7 to show drilling rate as a function of bit load with confining pressure as a parameter. This plot shows that as confining pressure increases, the rock becomes harder to drill. For example, the four curves (0, 1,000, 2,000 and 5,000 psi) could represent four different rocks of progressive hardness.

DRILLING RATE AS A FUNCTION OF CONFINING PRESSURE — DRAG BIT

Because of the difference in cutting action there was a possibility that variable confining pressure would not affect the drilling rate of a drag bit the same as it affects the drilling rate of a rock bit. In the cutting action of a rock bit, teeth or projections are pushed approximately perpendicularly into the surface of the formation. Chips are formed from the resulting stresses. The operation of a drag bit is different. A fixed blade scrapes against the formation pushing material ahead of it. This action is quite effective in soft, unconsolidated formations. Drilling rate of drag bits under variable confining pressure was affected in a similar manner to that of rock bits (Fig. 8).

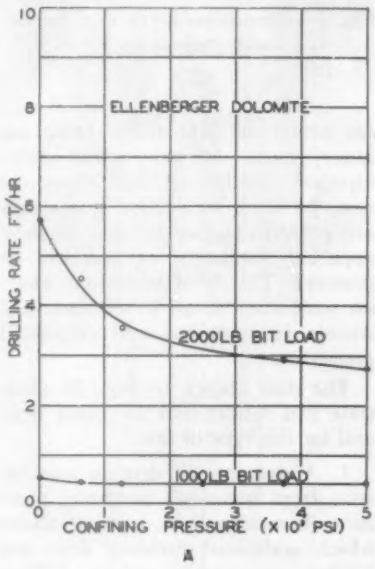
CORRELATION BETWEEN LABORATORY AND FIELD TESTS

Laboratory results showed that increasing confining pressure reduced drilling rate in most formations. A series of drilling tests were conducted in the field to determine if hydrostatic pressure affected drilling rate in a similar manner.

FIELD TESTS

Controlled drilling tests were run on 23 wells in the Leduc field of Canada by Imperial Oil Ltd. This field was selected for study because of their wide knowledge of geology and drilling practices in that area. Optimum drilling rates were established for each formation using conventional test methods. The effect of bit type, rotary speed, weight on bit, circulation rate, and fluid properties on rate of penetration was determined. A graph of drilling rate vs depth for each bit was made. Mid-point of the run was plotted in order to minimize effect of bit wear. An average penetration curve was computed from these data and its validity was checked by comparison with recent drilling experience.

Both micro-bit and field tests indicated that the variable lithology of some formations caused erratic penetration rates. Data from these tests were not used. The geologic interval, from surface to top of the Viking sand, was selected for analysis because it is a uniform column of 3,500 ft. The interval includes the Belly River, Lea Park, and Colorado formations. The average penetration rate curve and its equation is shown in Fig. 9A. Calculations are con-



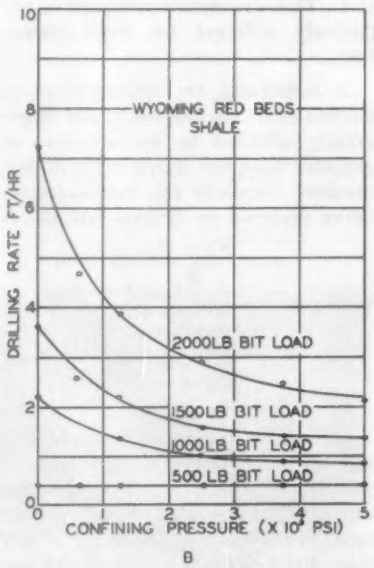


FIG. 6—DRILLING RATE VS CONFINING PRESSURE, VARIABLE BIT LOAD.

cerned with the section from surface to the Viking top. Data limits are indicated.

Correlation of laboratory and field data required several assumptions relating to field conditions. These are: first, drillability is uniform throughout; second, drilling rate is linearly related to table speed and weight on bit; third, crews are experienced and follow similar drilling practices; and fourth, circulation rate is sufficient to clean hole at the attained drilling rate. Field tests have indicated justification in using these assumptions.

Hughes OSC-3 bits were used in drilling the entire section. Water base-bentonite-natural mud was used for circulation, and properties were maintained as close as possible to those of water.

Laboratory Tests

Core samples from the Belly River, Lea Park and Colorado shales were drilled in the laboratory to determine the effect of confining pressure on drilling rate. These effects were comparable to those found in other soft shales. A composite curve was constructed from drilling rate data obtained from each formation (Fig. 9B). Points were selected from this curve for use in correlation with field results.

Correlation

Comparing drilling results obtained from 9-in. OSC-3 rock bits with those obtained from 1¼-in. diameter laboratory bits operating under different conditions requires certain assumptions. These are as follows:

1. For soft formations, drilling rate varies directly with rpm of bit and load per inch of bit diameter.

2. All other things being constant, the ratios of the drilling rates of two different bit types remain constant from formation to formation. (Considering here only softer formations.)

3. The percentage change in drilling rate due to a change in hydrostatic pressure is independent of the type of mud used.

Employing these assumptions, points from the composite curve of Fig. 9B were converted to comparable field conditions. These results are shown with the average field curve in Fig. 10. This close agreement indicates that the decrease in drilling rate in the field is probably due largely to the effect of the mud column pressure.

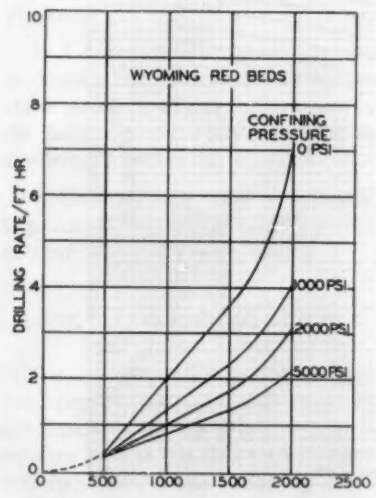


FIG. 7 — DRILLING RATE VS BIT LOAD.

DISCUSSION OF RESULTS

Estimation of Pressure Effects in the Field

A detailed theoretical analysis of rock failure based on Mohr's theory of failure is available.[5,6,7] This theory predicts that rock becomes harder to drill when subjected to a hydrostatic stress. There is, however, no procedure available for field use that will enable an evaluation of the relationship between hydrostatic stress and drilling rate. A means of estimating the effect of pressure on drilling rate may be obtained by using an empirical equation suggested by H. B. Woods and in addition, considering the laboratory test results. This equation is:

$$R = 24N\left(\frac{L}{3 \times 10^4 d}\right)^K \quad . \quad . \quad . \quad (1)$$

where

R = drilling rate—ft/hour
N = rpm of bit
L = load on bit
d = diameter of bit
K = is a constant for a given formation

For any given test all quantities are known except K. In the laboratory if N, L and d are held constant, changes in confining pressure will affect the value of K. Using the laboratory data and this equation, a plot of all K values vs pressure where each curve represents a different formation is shown in Fig. 11.

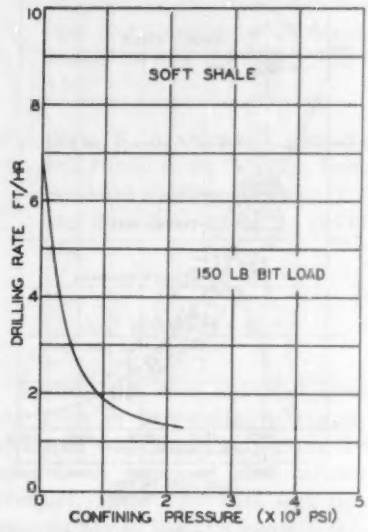


FIG. 8—DRILLING RATE VS CONFINING PRESSURE.

To illustrate the use of these curves an example is given:

Problem

A formation at 4,000 ft was drilled with a penetration rate of 30 ft/hour using a 9.6-lb mud, 9-in. bit, 20,000-lb bit load, and 120 rpm. If this same formation were drilled at atmospheric pressure, what would be the drilling rate using the same rpm, load, etc.?

Solution

For one given set of conditions, all variables of Equation 1 are known except K. This can be calculated. The pressure under the condition of this problem is 2,000 psi so that K becomes $K_{2,000}$. Substituting, Equation 1 becomes

$$30 = 24 \times 120\left(\frac{20{,}000}{3 \times 10^4 \times 9}\right)^{K_{2,000}}$$

from which $K_{2,000} = 1.75$. Enter Fig. 11 at point A, parallel the curves to pressure 0. $K_{atmos} = 1.36$ (point B).

Substituting $K_{atmos} = 1.36$, Equation 1 becomes

$$R = 24 \times 120\left(\frac{20{,}000}{3 \times 10^4 \times 9}\right)^{1.36}$$

$$= 83.5 \text{ ft/hour}$$

An increase in drilling rate of 53.5 ft/hour (178 per cent) is indicated if the hydrostatic pressure were reduced from 2,000 psi to atmospheric pressure.

This procedure has the following limitations:

1. The equation is empirical.

2. The results shown in Fig. 11 are plotted from average laboratory

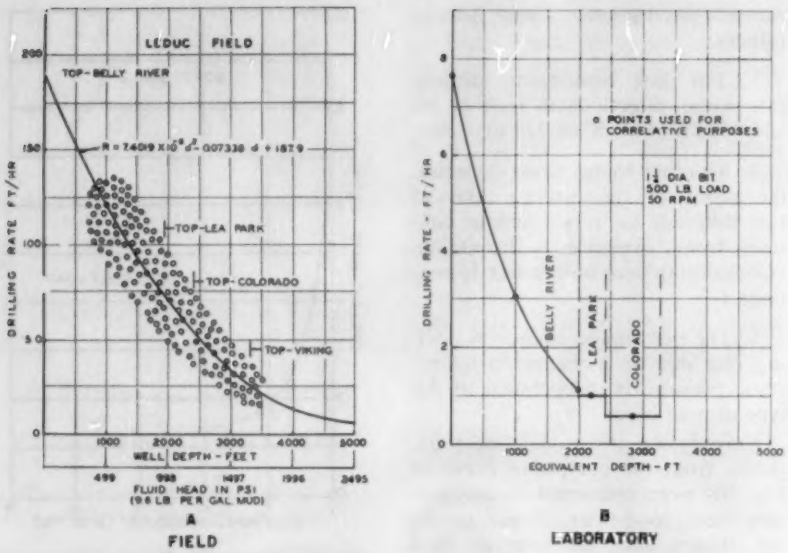


FIG. 9 — AVERAGE PENETRATION RATE CURVE.

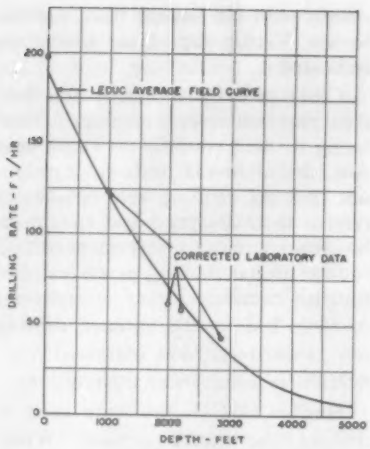


FIG. 10 — COMPARISON OF LABORATORY AND FIELD TESTS.

data. Some formations do not conform with these data.

3. Laboratory results do not provide for K values greater than shown. K values obtained from field data sometimes exceed these values.

4. If, in the process of reducing hydrostatic pressure, the drilling fluid is changed, there may be properties of the fluid which, in themselves, may alter drilling rates.

FORMATIONS NOT AFFECTED BY HYDROSTATIC PRESSURE

As previously stated, the drilling rate of one formation was not affected by the addition of confining pressure (Fig. 5). No explanation of this characteristic is attempted, however, the conditions of the tests are described. The formation was permeable, i.e., the drilling fluid was forced into the interstices of the material at some pressure within the test range.

Compression tests of permeable formations have been conducted by Bredthauer[5] and illustrate the condition of this test. For one series of tests, Bredthauer protected his cylindrical specimens with a plastic jacket so that the fluid producing the pressure could not enter the interstices of the material. The fluid acted against the outer surface of the cylinder so that the entire hydrostatic loading was constrained by the structure of the formation. In a second series of tests the specimen was not jacketed. The rock was saturated with fluid and exposed to confining pressure. The pressure within the formation was assumed equal to the confining pressure. For the jacketed specimen the differential compressive stress required to cause failure increased with increasing confining pressure. For the unjacketed specimen, the differential compressive stress required to cause failure did not increase with increasing confining pressure.

Most rocks drilled in the laboratory were impermeable to the circulating fluid within the range of confining pressures. The impermeable rock specimen in effect has a jacket which restrains fluid from entering the pores of the specimen. In these cases drilling rate was noticeably decreased as confining pressure was increased. This was shown in the majority of tests.

The drilling rate of one formation (Curve 3, Fig. 5) did not change with increased pressure. When broken open this formation was wet inside indicating a condition similar to that of the unjacketed cylinder.

These tests indicate that drilling rates in porous formations which are saturated with liquid may not increase if the pressure of the mud column is relieved.

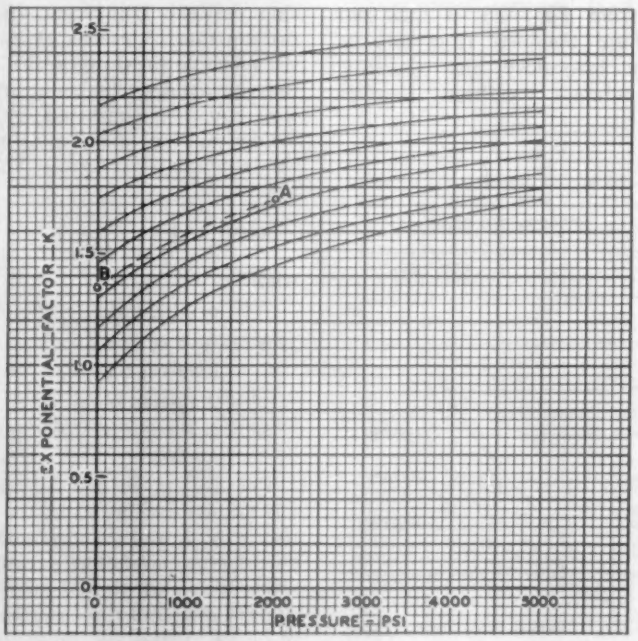


FIG. 11 — EXPONENTIAL FACTOR K AS A FUNCTION OF PRESSURE FOR SOME FORMATIONS.

Reduction of Pressure Effect

A better knowledge of the effect of mud column pressure on drilling rate will lead to improved bit design and drilling practice.

The use of air or gas as a circulating fluid has already demonstrated[9] that drilling rates can be increased over those obtained when using water or mud. In Pennsylvania during a two-well test, drilling time was reduced 270 hours from 510 hours where mud was used as a circulating fluid to 240 hours where air was used. The average depth of these wells was 7,000 ft. Results from laboratory tests indicate that a part of the increase in drilling rate associated with air circulation is due to relieving hydrostatic pressure. One method of reducing drilling costs is by developing practices and procedures which will allow the use of air or gas in areas where they cannot now be used.

A second method of relieving hydrostatic pressure has been described by Bobo, Hoch and Ormsby.[10] They used an air-mud mixture to reduce fluid density.

Other methods may be developed to reduce pressure in the vicinity of the bit while maintaining a full fluid column through the use of a pack off system.

CONCLUSIONS

1. Laboratory tests have indicated that in most formations drilling rate is decreased by increasing confining pressure.

2. Field tests have indicated that in most formations drilling rate is decreased by increasing hydrostatic pressure.

3. A correlation of laboratory and field tests has indicated that hydrostatic pressure affects drilling rate in the field approximately the same as confining pressure in the laboratory.

4. Drilling costs may be reduced if practical methods of relieving mud column pressure are developed.

ACKNOWLEDGMENT

The authors wish to thank both the Hughes Tool Co. and Imperial Oil Ltd. Producing Dept., for permission to publish this paper. They feel indebted to the following companies for supplying cores used in laboratory experiments: Magnolia Oil and Refining Co., Atlantic Refining Co., Humble Oil and Refining Co., Phillips Petroleum Co., Shell Oil Co., and Imperial Oil Ltd.

In addition, they also wish to thank the following for valuable help: H. B. Woods, Erwin A. Morlan, and J. G. Eenink, Hughes Tool Co.; V. J. Moroney, Charles Visser, and R. K. Irvine, Imperial Oil Ltd.; and Peter A. Szego, formerly with Rice Institute, Houston, Tex.

REFERENCES

1. Adams, F. D., and Nicolson, J. T.: "An Experimental Investigation Into the Flow of Marble," *Proc.* Royal Society of London (1921) Series A, **195,** 363.

2. Griggs, D. T.: "Deformation of Rocks Under High Confining Pressure," *Jour. of Geology* (1936) **44,** 541.

3. Handin, John: "An Application of High Pressure in Geophysics: Experimental Rock Deformation," *Trans.* ASME (1953) **75,** 315.

4. Bureau of Reclamation, U. S. Department of the Interior, "Physical Properties of Some Typical Foundation Rocks," Concrete Laboratory Report No. SP-39 (Aug. 13, 1953).

5. Kühne, I. G.: "Die Wirkungsweise von Rotarymeiseln un anderen drehenden Gesteinsbohrern," Sonderdruck aus der Zeitschrift, Bohrtechnik-Brunnenbau, Heft 1-5 1952.

6. Szego, P.: Translation — "The Mode of Operation of Rotary Bits and Other Rotary Rock Drills" by I. G. Kühne.

7. Cunningham, R. A.: "The Effect of Hydrostatic Stress on the Drilling Rates of Rock Formation," Unpublished MS Thesis, Rice Institute, 1955.

8. Bredthauer, R. O.: "Strength Characteristics of Rock Samples Under Hydrostatic Pressure," Unpublished MS Thesis, Rice Institute, 1955.

9. Magner, H. J.: "Lost Circulation and Completion Problems Eased," *World Oil* (Jan., 1955) 116.

10. Bobo, R. A., Ormsby, Geo. S., and Hoch, R. S.: "Phillips Tests Air-Mud Drilling," Part 2, *Oil and Gas Jour.* (Feb. 7, 1954) 104.

APPENDIX*

Earlier tests cited indicated drilling rates in permeable formations saturated with liquid might not be affected by increased mud column pressure. These tests were with formations having low and variable permeabilities. The degree of saturation was impossible to determine. Studies in which permeability could seriously be considered as a factor were delayed. Later Berea sandstone (permeability 100-300 md) was tested and found to be satisfactory as a test material.

Drilling rate tests were made using Berea sandstone cores saturated with water and having all surfaces of the core exposed to the confining pressure of the drilling chamber. The fluid pressure in the interstices of the core was free to assume a pressure equal to that of the confining pressure. No measurable decrease in drilling rates were obtained with increased confining pressures.

Although pressure alone does not affect drilling rates in permeable formations, under certain conditions pressure is responsible for a very large decrease in drilling rates. Consider a hole drilled into a permeable formation which contains fluid at a pressure P_1. Let the drilling fluid pressure P_f be greater than P_1 and the pressure difference $P_f - P_1 = \triangle P \geq 0$ psi. Under these conditions the drilling fluid would tend to move into the interstices of the formation. This condition was approximated as shown in Fig. 12. All surfaces of the core sample except one were exposed to fluid. One surface was exposed to the atmosphere so that fluid was forced through the core to the atmosphere.

Under these conditions the pressure drop across the core was as-

*These results were obtained late and are added to original paper.

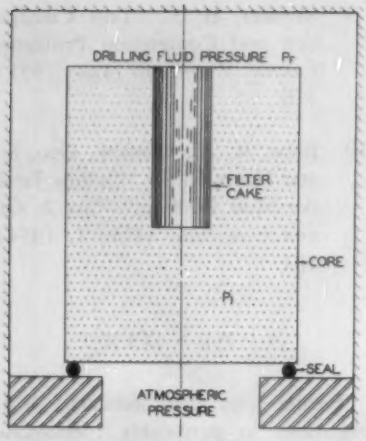


FIG. 12 — TEST ARRANGEMENT.

sumed to be equivalent to the pressure difference $\triangle P$. Clear water used as drilling fluid moved through the formation fast enough to prevent pressure from building up. No change occurred in drilling rates. A low water loss mud used as drilling fluid formed a filter cake on the high pressure side of the core. Pressures could be built up. Drilling rates were reduced greatly as shown in Fig. 13. Apparently the mud cake formed on the surface of the rock became very strong and tough with the large pressure difference tending to hold the cake tightly against the face of the rock. If a portion of this cake was removed, large pressure differences must have caused very rapid replacement of new cake in its place.

To drill hole in the presence of a tough filter cake, a rock bit tooth must first penetrate the cake and then, once through it, cause a chip to form. Before the chip can be removed it must work its way up through the cake into the circulating system. If the chip is held in place by the filter cake, subsequent teeth simply fracture the chip into smaller chips until the cake probably becomes a mixture of mud and very fine cuttings. The net effect is that the bit is running on a "cushion" of filter cake and cuttings with a large decrease in drilling rates as indicated in Fig. 13.

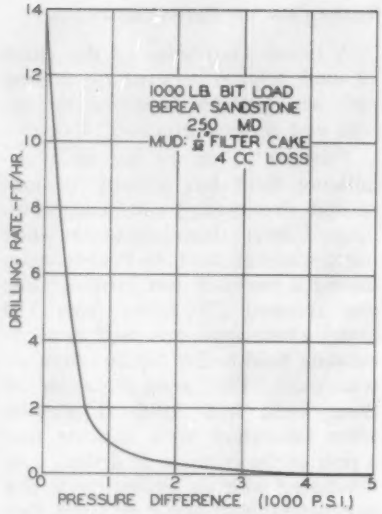


FIG. 13 — DRILLING RATE VS PRESSURE DIFFERENCE.

At present, plans are being made to: (1) vary both fluid pressure on the formation and drilling mud pressure; and (2) test the effect of jet velocities on the filter cake.

DISCUSSION

P. L. MOORE
JUNIOR MEMBER AIME

HUMBLE OIL & REFINING CO.
HOUSTON, TEX.

The fact that fluid column pressure, or, as referred to in this paper, hydrostatic pressure has an effect on drilling rate in some rocks or formations has been established rather conclusively. Humble has observed this effect in laboratory and field drilling and several discussions or papers have included data showing that there are decreases in drilling rates in various rock when hydrostatic pressure is increased. However, as yet there does not seem to be any agreement as to the cause of slower drilling rates at higher pressures.

There appears to be some relationship between permeability and this effect, and some tests have shown that various rocks under increased pressures were harder to fracture. In addition, this paper mentions a relationship with density. In general, the impermeable rocks, at least in laboratory drilling, are the ones more susceptible to hydrostatic pressure effects. Logical reasons for this effect would be that across the minute particle of rock being drilled there exists enough of a pressure differential for compaction; however, if the rock is saturated prior to test drilling this differential should not exist. Therefore, following this line of thinking, a rock should always be saturated prior to test drilling in the laboratory, that is, if it is assumed field formations are saturated.

Two ways of saturating rock in the laboratory are pressure or vacuum saturating. The latter method should offer the best means for complete saturation; however, there is some question even then if complete saturation of all pore spaces takes place. Based on this doubt, it may be that laboratory rocks are never comparable to field formations. This is assuming the field formations are saturated. If they are not, it would be difficult to even know the degree of saturation in any field rock so it could be similated in laboratory drilling. To sum up this thought, if a rock is completely saturated when drilling then the equalization of pressures across any fractured particle should be practically instantaneous, and it would make no difference if it was permeable or impermeable. When pressures on rocks have been increased, it has been found in some cases that rocks failed at higher compressive stress indicating that the more impermeable rocks may drill slower at higher pressure because they are more affected by the increased pressure.

Although data from this paper provide a strong argument for the mentioned relationship between drilling rate and rock density, none of Humble's tests have shown that this effect exists. Examples are soft Frio sand cores, a Gulf Coast area producing formation, and Lueders limestone, a quarry rock, both showed no effects from hydrostatic, while harder shales and Carthage marble, another quarry rock, were drilled slower at higher pressures.

Field observations have shown that as the mud density is increased, thereby increasing the hydrostatic

pressure on the formation, there is a reduction in drilling rate. However, in short interval field tests, where the weight of small batches of mud was varied over a wide range, it was observed that the drilling rate was reduced considerably as the mud density was increased. The size of the test batches was such that the effective hydrostatic pressure on the mud column was not appreciably effected.

The empirical formula used to solve for drilling rates at different pressures resulted in the calculation of points almost on the actual drilling rate vs depth curve. The only question is on the correlation between large and small bits. In this paper bit diameters are used; however, considering the part of the bit that constitutes a cutting surface, it seems that the ratio between the two should be a figure between bit diameter and area. The reason that it had no effect in this formula, if it should be a higher number than just a ratio of diameters, probably lies in the calculation and use of K which would, so long as it is a linear relationship between bit size, compensate for any error.

It is interesting to note the good correlation of field and laboratory data in this paper, and the authors are to be complimented for their time and efforts permitting these correlations to be made. Through the combined efforts of all companies doing research in this field, it is hoped that methods and techniques will soon be devised to overcome the problem of slower drilling with increased pressure.

AUTHORS' REPLY to PRESTON L. MOORE

The relationship of the pressure effect on drillability of formations referred to by Preston L. Moore has been found in most cases where the formations are impermeable under laboratory test conditions (see Fig. 4A). Many formations have been found which do not satisfy this conclusion (see Fig. 5). At least part of the deviation is believed to be due to the variation in the permeability of some formations. Those formations named by Moore could very well be in this group.

The desirability of saturating the laboratory core samples may be doubtful in some cases. First, the exact degree of saturation in the field may be unknown, making laboratory duplication impossible. Second, if a pressure difference exists between the formation fluid pressure and mud column pressure, the rate of penetration of the mud (assuming no filter cake) will be in part a function of the permeability. If the permeability is high so that the mud moves into the formation rapidly, the rock bit drills a formation which is saturated with a fluid at practically the same pressure as the mud column. If the permeability is low so that the mud moves into the formation as slowly or more slowly than the rock bit drills into the formation, then the rock bit is drilling a formation which has a high pressure acting against the surface of the rock. With this line of thinking, it may not be desirable to saturate the laboratory cores.

Moore questions the use of bit diameters instead of areas in the correlation between large and small bits. He is right in his thinking that a figure between the two should be used. Within the range of our laboratory tests on various bit sizes, this figure is closer to bit diameter; in fact, so close that we have used it as the diameter. ★★★

AIME, PETROLEUM BRANCH MAJOR MEETING SCHEDULE

1956—Feb. 19-23, Annual AIME Meeting, Hotel Statler, New York City.

1956—March 29-30, "Petroleum Conference, Economics and Valuation," Statler-Hilton Hotel, Dallas.

1956—May 14-15, "Formation Fracturing Symposium," Wichita, Kans.

1956—May 17-18, Joint Meeting of Rocky Mountain Petroleum Sections of AIME, Gladstone Hotel, Casper, Wyo.

1956—Nov. 19-20, "North Texas Secondary Recovery Symposium," Wichita Falls, Tex.

1956—Oct. 14-17, Petroleum Branch Fall Meeting, Biltmore Hotel, Los Angeles.

1957—Feb. 24-28, Annual AIME Meeting, New Orleans.

1957—Oct. 6-9, Petroleum Branch Fall Meeting, Dallas.

1958—Feb. 16-20, Annual AIME Meeting, Hotel Statler, New York City.

1958—Oct. 12-15, Petroleum Branch Fall Meeting, Houston.

1959—Feb. 15-19, Annual AIME Meeting, San Francisco.

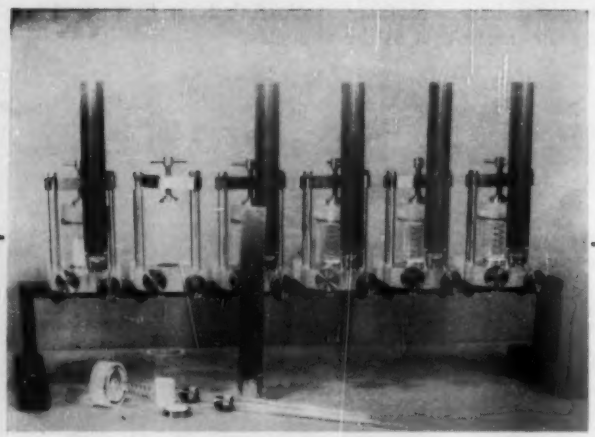
1959—Oct. 11-14, Petroleum Branch Fall Meeting, Dallas (tentative).

1960—Feb. 14-18, Annual AIME Meeting, Hotel Statler, New York City.

1961—Feb. 19-23, Annual AIME Meeting, St. Louis.

1962—Feb., Annual AIME Meeting, New York City.

1963—Feb. 17-22, Annual AIME Meeting, Dallas.



Capillary Pressure Cells

INSTRUMENTS for the Oil Industry

CORE ANALYSIS and

RESERVOIR ENGINEERING

Production model instruments or custom designed laboratory installations

Ruska Instrument Corporation

4607 MONTROSE BLVD. HOUSTON 6, TEXAS

ADVERTISERS' INDEX

Aldrich Pump Co. 7
Harris D. McKinney Industrial Adv., Inc., Philadelphia

American Potash & Chemical Corp. 41
The McCarty Co., Los Angeles

Baker Oil Tools, Inc. 4, 5
Martin-Ripley Adv., Los Angeles

Baroid Div., National Lead Co. 43
Rittenhouse & Co., Inc., Houston

B & W, Inc. 39
Brennan Adv. Agency, Houston

Byron Jackson Div., Borg-Warner Corp. . . . 23
Ramsey, Brown & Co. Adv., Los Angeles

Clark Bros. Co. 24, 25
Harold Warner Co. Adv., Buffalo, N. Y.

Cooper-Bessemer Corp., The 21
The Griswold-Eshleman Co. Adv., Cleveland

Core Laboratories, Inc. 2
Duvall Williams Adv., Dallas

Dowell Incorporated 8
MacManus, John & Adams, Inc., Adv., Bloomfield Hills, Mich.

Eastman Oil Well Survey Co. 45
Ted Workman Adv., Dallas

Guiberson Corp. . . . . Third Cover
Rogers & Smith Adv., Dallas

Halliburton Oil Well Cementing Co. 1, 47
Hill & Christopher Adv., Los Angeles

Hughes Tool Co. 33, 34
Foote, Cone & Belding Adv., Houston

Hydril Co. 26
Ramsey, Brown & Co. Adv., Los Angeles

Johnston Testers, Inc. 6
Bruce B. Brewer & Co., Kansas City, Mo.

Lane-Wells Co. . . . . Fourth Cover
Darwin H. Clark Co. Adv., Los Angeles

Lufkin Foundry & Machine Co. 44
A. E. Cudlipp, Lufkin

McCullough Tool Co. 32
Raymond O. Perry Adv., Los Angeles

National Tank Co. 48
Gibbons Adv. Agency, Inc., Tulsa

Otis Pressure Control, Inc. 42
Dan Goodrich Adv., Dallas

Professional Services 36, 37

Ruska Instrument Corp. 1A
Brennan Adv. Agency, Houston

Schlumberger Well Surveying Corp. . . Second Cover
Rives, Dyke & Co. Adv., Houston

Tretolite Co. 37
John C. Fellows Co. Adv., Los Angeles

Visco Products Co., Inc. 22
Armstrong Adv. Agency, Chicago

Yale Machine Works 40
W. L. Culver Adv. Service, Houston

HOLDS PRESSURES Automatically

GUIBERSON Type E TUBING STRIPPER

FOR LOW AND MEDIUM PRESSURES

Low in height and compact, this new Guiberson stripper speeds up running or pulling tubing because it seals automatically. Rubber requires no tightening or adjustment. Cup-shaped rubber is specially designed to be tear resistant — specially compounded to resist damage from oil, gas or well fluid. Reinforced with steel wires and bushing.

Bayonet-type latch on cover plate makes it easy and quick to remove or install rubber. Handles lock the cover on the body. Cover plate accommodates Guiberson Tubing Spider. Body may be tapped for two 2″ side outlets on special order. Pressure rating, 750 p.s.i. working pressure, 1500 p.s.i. test pressure. For 2″, 2½″ and 3″ tubing, and for flange sizes 6″-400, 6″-600, 6″-900, 8″-400 and 8″-600.

THE GUIBERSON CORPORATION

ESTABLISHED 1919 • DALLAS, TEXAS, U. S. A.

Sold By Leading Oil Field Supply Stores Everywhere

PENETRATION'S

ONLY PART OF IT!

KONESHOT®

shaped-charge perforating

GETS THE RESULTS

YOU'RE AFTER

That's because KONESHOT—Lane-Wells special shaped-charge perforating—gives you the *accuracy* of Lane-Wells famous depth-measurement system to deliver the penetration you want deep into the exact place you've ordered it put. That's what makes KONE-SHOT the unbeatable combination—penetration plus accuracy!

LANE-WELLS COMPANY

Write for further information on LANE-WELLS KONESHOT

Tomorrow's Tools—Today!®

KZ-84-A

General Offices, Export Office and Plant • 5610 So. Soto St. • Los Angeles 58, California

Los Angeles • Houston • Oklahoma City • Lane-Wells Canadian Co. in Canada • Petro-Tech Service Co. in Venezuela